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AGARD REPORT 824

Propulsion and Energy Issues for the 21st Century

(les Enjeux de la propulsion et de l'énergétique à l'aube du 21ème siècle)

NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization

Organisation du Traité de l'Atlantique Nord

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Propulsion and Energy Issues for the 21st Century

(AGARD R-824)

Executive Summary

This report provides a review and capability projection for a number of propulsion technology topics that could ensure and significantly enhance NATO air dominance well into the next century.

The main topic deals with a "Hypersonic Air Breathing Missile" that discusses in an exemplary way the military uses and technology requirements for a new weapon with unprecedented capabilities. This hypersonic missile, traveling at speeds between Mach 6-8, could be used as a medium distance weapon against hardened ground targets, very high value aerial targets, or time critical targets such as mobile theater ballistic missile launchers. Launched from the ground or air, it would cover up to 1500 kilometers in about 15 minutes and be virtually indefensible due to its hypersonic speed. The critical technology is the scramjet engine operating on a liquid hydrocarbon fuel that permits immediate launch and full control of engine power throughout the flight path. Detailed application and technology requirements are described.

Maintaining air dominance in the battlefield is predicated on controlling the air space with a variety of air vehicles and missile systems; these are generally powered by gas turbine engines and rocket motors. Gas turbines will continue to be the most cost effective propulsor that can provide the necessary power for manoeuverability, armament control and mission flexibility. Rocket engines offer very high specific power that is a fundamental requirement for many types of missiles and boosters. A technology development survey is given that briefly describes the considerable improvements to be expected in performance and economics. Doubling the range and halving the reaction time for fighter and global strike aircraft, and increasing by 50% the reach of global transport aircraft are well within sight.

Three examples are given that introduce or foster new types of propulsion. The pulse detonation wave engine offers a marked increase in efficiency and a simplification of design over current rocket and ramjet engines. Gun projectiles may be driven electrically or by liquid charges, both of which promise to overcome the limitations posed by high energy solid propellants. Laser power beaming offers a means of transferring energy to vehicles over large distances. Despite the immense technological complexity, it may open entirely new roads for powering aerial vehicles in the more distant future. First applications may be in repowering satellites for extended operations and shifting of orbits.

These technology and application reviews were originally developed under the auspices of the AGARD Aerospace 2020 Study. They are based on input from the AGARD Propulsion and Energetics and other Panels, the Aerospace Applications Study Committee of AGARD, and many contributions from outside AGARD. This report is but one example of the value that AGARD has provided to the military community, often at very short notice, over the past 45 years of its history.

Les enjeux de la propulsion et de l'énergétique à l'aube du 21ème siècle
(AGARD R-824)

Synthèse

Ce rapport fournit une analyse et des prévisions concernant un certain nombre de questions dans le domaine des technologies de propulsion qui sont susceptibles d'assurer, voire même renforcer la situation de supériorité aérienne de l'OTAN, pendant une bonne partie du 21ème siècle.

Le futur missile aérobie hypersonique constitue le principal sujet du rapport. Il sert de base, à titre d'exemple, pour la discussion des applications militaires, ainsi que pour les spécifications technologiques d'une arme nouvelle, sans équivalent à l'heure actuelle. Ce missile hypersonique, évoluant à des vitesses comprises entre Mach 6 et Mach 8, pourrait être déployé à distance moyenne contre des cibles durcies au sol, ainsi que contre des cibles aériennes de grande valeur et des cibles dont le temps de démasquage est très court, tels que les lanceurs mobiles de missiles balistiques du théâtre. Lancé du sol ou d'une plateforme aérienne, il parcourrait jusqu'à 1500 kilomètres en 15 minutes environ et serait très difficile à neutraliser en raison de sa vitesse hypersonique. La technologie de pointe est le statoréacteur à combustion supersonique à propergol liquide hydrocarboné, autorisant le lancement instantané et la régulation du régime moteur en fonction de la trajectoire.

Le maintien de la supériorité aérienne passe par la maîtrise de l'espace aérien via un éventail de véhicules aériens et de systèmes de missiles; ceux-ci sont normalement propulsés par des turbomoteurs et des moteurs-fusée. Les turbomoteurs resteront les propulseurs de choix, car ils représentent le moyen le plus efficace par rapport au coût de fournir la puissance propulsive nécessaire pour assurer la souplesse dans la conduite des missions, la manœuvrabilité et la commande des systèmes d'armes. Les moteurs-fusée offrent l'énergie spécifique très élevée indispensable pour bon nombre de missiles et de propulseurs d'accélération. Un aperçu de l'évolution des technologies est donné avec une brève description des améliorations considérables qui sont escomptées en termes de performances et d'économies. Doubler la distance franchissable, réduire de moitié les délais de réaction des avions de combat et d'appui tactique et augmenter de 50% la rayon d'action des avions de transport sont des objectifs tout à fait réalisables.

Trois exemples de techniques sont donnés. Elles permettent d'envisager de nouveaux types de propulsion. Le moteur à onde de détonation offre la meilleure efficacité et une conception simplifiée comparé aux moteurs-fusée et aux statoréacteurs actuels. Les projectiles de canons pourront être propulsés électriquement ou par charge liquide; ces deux techniques permettront de s'affranchir des limitations imposées par les propergols solides à haute énergie. Les faisceaux laser permettront de transmettre de l'énergie aux véhicules sur de grandes distances. Malgré sa complexité technologique impressionnante, cette technique pourrait ouvrir de nouvelles voies, dans un avenir plus lointain, à la propulsion de véhicules aériens. Les premières applications pourraient concerner la réalimentation des satellites pour la prolongation des opérations et le changement d'orbite.

Ces analyses des technologies et des applications possibles ont été élaborées pour la première fois sous l'égide de l'étude "Aerospace" 2020" de l'AGARD. Elles sont basées sur des contributions de différents Panels de l'AGARD et en particulier le Panel de propulsion et d'énergétique et le comité d'études en vue d'applications aérospatiales, ainsi que sur de nombreuses autres contributions de sources extérieures. Ce rapport n'est qu'un exemple parmi d'autres des ouvrages de très grande valeur que l'AGARD a fourni à la communauté militaire, souvent à très bref délai, au cours de ses 45 années d'existence.

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AGARD R 810, January 1997 (NATO Unclassified)

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Sensors and Propagation Panel (SPP)
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List of Authors/Editors

	Chapter
Mr. Robert E. Henderson Universal Technology Corp. 4031 Colonel Glenn Highway Dayton, OHIO 45431-1600, United States	1/4
Mr. Paul Kuentzmann Office National D'Etudes et de Recherches Aerospatiales (ONERA) B.P. 72, F-92322, Châtillon Cedex, France	1
Mr. Hans-Ludwig Besser Bayern-Chemie GmbH, Werk Ottobrunn Abteilung E, Postfach 1047, 85501 Ottobrunn, Germany	1
Dr. Frank D. Stull Universal Technology Corp. 4031 Colonel Glenn Highway Dayton, OHIO 45431-1600, United States	1
Dr. Paul Waltrup Applied Physics Laboratory, Johns-Hopkins University Building 6, Room 355 Johns-Hopkins Road Laurel, MARYLAND 20723-6099, United States	1
Dr. Terry Ronald Air Force Wright Laboratory, Aero Propulsion & Power Directorate Wright-Patterson Air Force Base, OHIO 45433 7521, United States	1
Mr. Glendon Lazalier Sverdrup Technology, Inc. AEDC Group MS-9109 Arnold AFB, TENNESSEE 37389, United States	1
Mr. Richard J. Hill Air Force Wright Laboratory, Aero Propulsion & Power Directorate Wright-Patterson Air Force Base, OHIO 45433 7251, United States	2
Mr. Anthony J. Cifone Naval Air Warfare Center, Aircraft Division, Propulsion & Power Patuxent River, MARYLAND 20670-5304, United States	2
Mr. Lee Meyer Air Force Phillips Laboratory, Rocket Propulsion Directorate Edwards Air Force Base, CALIFORNIA 93524, United States	3
Dr. Raymond Edelman Boeing, Rocketdyne Division, Dept. 909, IA06 6633 Canoga Park, CALIFORNIA 91309, United States	4
Dr. Rose Pesce-Rodriguez Weapons Technology Directorate, Army Research Laboratory AMSRL-WT-PC, Aberdeen Proving Ground MARYLAND 21005-5006, United States	5
Dr. Willem J. Kolkert Pulse Physics Laboratory, TNO Prins Maurits Laboratory Delft, The Netherlands	5
Dr. Harold E. Bennett Bennett Optical Research, Inc. 139 Balsam Street Ridgecrest, CALIFORNIA 91309, United States	6
Dr. Klaus C. Schadow Naval Air Warfare Center, Weapons Division First Administration Circle, MS 104D China Lake, CALIFORNIA 93555-6001, United States	6

Preface

Originally, the material for this report was generated under the auspices of the AGARD Aerospace 2020 study and would be published in parts within two discrete volumes. The Propulsion and Energetics Panel (PEP) felt that the individual chapters were closely related, encapsulated the essence of the PEP terms of reference and were worthy of publication as a separate volume aimed specifically at propulsion specialists. The collection of these 6 chapters provides an overall projection and perspective of the propulsion and energy technological capabilities that could be made available over the next 25 years.

Considerable editing has been made to minimize overlap and redundancy throughout this report. Where overlap does occur, it is intended to reinforce the critical technology areas and issues that require specific attention if one is to successfully develop, demonstrate and ultimately field advanced aerospace systems.

This report represents the contributions of many authors from across the relevant technical panels of AGARD, the Aerospace Applications Study Committee and expertise drawn from specific individuals who have spent many years immersed in these technologies. We are grateful to all contributors for their willingness to communicate their experience and knowledge.

Robert E. Henderson, Editor
Don M. Rudnitski, PEP AHC2020 Chairman

CHAPTER 1

HYPERSONIC AIR BREATHING MISSILE

Robert E. Henderson
Universal Technology Corporation
Editor

ABSTRACT

Under the auspices of the AGARD Aerospace 2020 Study, the Propulsion & Energetics Panel (PEP) was identified as the lead Panel for the technology push topic on the subject of "Hypersonic Air Breathing Missile", a scramjet propelled weapon system which can operate on liquid hydrocarbon fuel and achieve mission flight speeds as high as Mach 8. A broad technology base for the scramjet propulsion system has already been developed; however, a number of critical technology issues and requirements must still be addressed. The key element of this hypersonic weapon system is the liquid hydrocarbon fueled scramjet engine, recognized as the most promising and effective air breathing propulsion technology for hypersonic flight at Mach numbers of 5-8. Some ground testing has been conducted with a kerosene-fueled scramjet engine; however, the more expensive flight testing of such a vehicle is yet to be accomplished. Considerable research has been conducted over the past ten years on the hydrogen fueled scramjet with a principal focus on its application to man-rated hypersonic weapon systems, reconnaissance vehicles and space launchers spanning the flight Mach number range of 10-15. This Aerospace 2020 Study topic, however, concentrates on the application of the scramjet propulsion concept using high heat sink, liquid hydrocarbon or endothermic fuels which offer significantly enhanced mission potential for future military tactic al missiles. This topic attempts to define the critical technology development areas and issues which require specific attention if one is to successfully develop, demonstrate and ultimately field such a weapon system.

EXECUTIVE SUMMARY

VISION

Provide a high speed, fast response missile propelled by an air breathing engine using storable liquid hydrocarbon fuels and capable of fulfilling critical missions for extended air defense, reconnaissance, threat suppression and space access at an economically viable cost.

The Supersonic Combustion RAMJET (SCRAMJET) has been recognized as the most promising air breathing propulsion technology for hypersonic flight (Mach number above 5) because it has a very high speed theoretical operational limit, depending upon the fuel used. Considerable research has been conducted during the past ten years on the hydrogen fueled scramjet, with significant attention focused on new generations of space launchers. Some ground testing has also been conducted with a kerosene-fueled scramjet engine. Application of the scramjet concept using high heat sink, hydrocarbon or endothermic fuels offers significantly enhanced mission potential for future military tactical missiles (Figure 1).

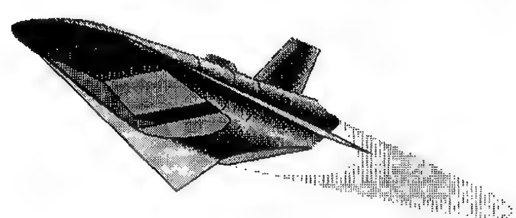

Figure 1 Scramjet Missile Concept

SCOPE

This technology push topic is based on the development and application of the scramjet propulsion concept, an enabling technology which will permit air vehicle flight speeds up to Mach 8 (2.4 km/s).

* Liquid fuel ramjet:
  - Mach 2.7-3.2 was achieved by the operational Bomarc missile -- U.S. circa 1960
  - Mach 3.5 is achievable by current operational missiles -- French ASMP, circa 1988 [Ref. 1, 2]
  - Mach 4.5 was achieved by the experimental Advanced Strategic Air Launched Missile (ASALM) – U.S. circa 1980
  - Mach 5.5 has been achieved by experimental vehicles -- French Stataltex, circa 1965 [Ref. 3]

* Ducted rockets and ramrockets:
  - Mach 3.5 has been demonstrated -- French MPSR 1 & 2, circa 1985 & 1995, "Rustique"
  - Mach 4+ can be expected in the near future

* Scramjets and dual-mode ramjets:
  - Very few flight tests (hydrogen fuel)
  - Mach 5 operation achieved during a short time (tethered scramjet) -- France/Russia 1990/94/95

The scramjet concept is the most promising and challenging air breathing propulsion technology approach for flight vehicle operation at Mach numbers above 5. Furthermore, the scramjet propelled vehicle concept was favorably endorsed under the recently published US Air Force study entitled "New World Vistas", conducted in 1995 [Ref. 4]. A number of additional references can be drawn from recent AGARD Symposia and Lecture Series which add credence to the viability of this study topic and the enhanced weapon system capability it can provide the NATO Military Commanders in responding to future potential adversarial actions [Ref. 5, 6, 7, 8, 9]. Furthermore, it should be noted that much of the material discussed/presented herein is the result of extensive interviews and written inputs from a large number of experts across the NATO propulsion community.

SYSTEM OPERATIONAL PAY-OFF

Initial applications of the hydrocarbon-fueled scramjet could be for aircraft-launched high speed missile systems, both medium and long range (750-2500 km), for time critical ground and aerial targets and strategic target recognition. Beyond these possibilities, development of hypersonic aircraft can also be considered for global fast reaction reconnaissance missions and for future low cost space launch vehicles. Expected operational gains relative to that offered by conventional ramjet and rocket missile systems can be quantified as follows:

Rocket efficiency	Factor of 3-10 improvement in specific impulse (Isp)
Increased cruise range	Factor of 2
Reduced response time	Mach 8 – 1200 km in 15 minutes
Affordable force multiplication	Halve missile size - launch from F-15, F-16 or 2x bomber loadout

MILITARY NEED

The primary mission offered by this technology push and representing a substantial improvement relative to current weapon system capability is the Fast Response Missile. This particular study report will focus on the technology development and application issues of this important mission for a hypersonic missile system, a capability which can be realized by the year 2020. A number of NATO-defined mission areas can be supported by such a weapon system:

- Air-to-Surface Tactical Missiles
- Counter Air Tactical Missiles
- Mobility
- Reconnaissance/Surveillance/Intelligence RSI)
- Suppression of Enemy Air Defense (SEAD)
- Theater Missile Defense (TMD)

Of particular interest with a missile of this type is the ability to launch such a weapon from a fighter platform, such as an F-15 or F-16 aircraft. Both of these aircraft could accommodate this hypersonic missile; however, the weight of such a weapon would likely limit the F-16 to a centerline launch only. Initial estimates on weight for a Hypersonic Air Breathing Missile (HABM) launched from either of these aircraft is in the range of 1400-1600 kgs. This would provide a medium range capability, after missile launch, of 1200-1500 kms. Figure 2 depicts an artist's impression of an F-15 aircraft with two hypersonic missiles of this type installed on its inboard launch rails. For optimum mission range, missile booster launch would occur at

high subsonic to low supersonic aircraft flight speeds and at altitudes of 9-12 km. It is expected that the missile booster would rapidly accelerate the missile to scramjet takeover speeds in the Mach 5.5-6.0 range. If direct transition to scramjet propulsion is not possible, the air breathing engine would have a dual-mode ramjet/scramjet capability during final post boost acceleration to a mission cruise Mach number of 7-8. This could place the missile on target within 10-15 minutes after launch, depending upon the missile flight path taken.

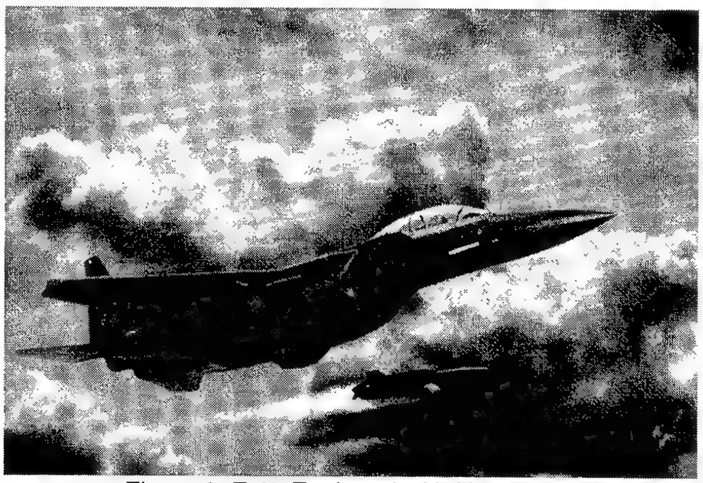

Figure 2 F-15 Equipped with Hypersonic Air Breathing Missiles

Two basic missile classes are proposed:

* Hypersonic Long Range Cruise Missile or Drone for air-to-surface, reconnaissance, surveillance and intelligence gathering. The principal technology challenge is the dual mode ramjet/scramjet engine, the rocket booster, and the materials and thermal management technology issues related thereto. Other important technologies are sensors and terminal guidance, which are especially important in order to assure high precision on the target. This class will provide a fast response for time-critical targets or missions, will simplify the guidance problem, and will increase the penetration capability. Furthermore, this latter capability can be achieved, even with progress in anti-stealth technologies, by flying at high speed (Mach 6 - 8) and at high altitude (30 - 40 km) in order to pass over and/or out-maneuver the classical surface-to-air defense systems.

* Anti Tactical Ballistic Missiles (ATBM) with a sufficiently fast response time to counter an enemy ballistic missile threat at ranges of 400-1000 km. This class would be particularly effective in countering the proliferation of Tactical Ballistic Missiles (TBM) by attacking a TBM threat prior to or during its launch phase. Ascent phase interception of an enemy TBM, however, would require a very short response time with target detection/guidance acquisition literally within seconds of TBM launch. Terminal maneuvering of the ATBM in order to intercept a just-launched TBM will be critical. Hence, the ATBM is at its greatest effectiveness when launched against the enemy threat during TBM setup and preparation for launch. These time critical surface targets, by definition, present a small window of opportunity for conventional attack. Target sets include mobile units, particularly mobile theater ATBM launchers. Once loaded, identified and targeted by external means, ground based, sea based, or tactically air launched hypersonic weapons could be utilized against a designated hostile target to pre-empt the launch or to retaliate against a hostile launcher shortly after launch. Time and precision are key elements in accomplishing the mission. External targeting must be available and quickly downloaded into the hypersonic missile's guidance system for launch and mid-course guidance. Furthermore, accurate terminal guidance is required to ensure maximum accuracy in the end game for assured target destruction. One possible mission scenario for the ATBM is illustrated in Figure 3. This figure graphically describes the time line (4 minutes) for a Mach 8 Scramjet powered missile from target detection to impact based on a launch range of approximately 500 km. Of particular importance is the substantially reduced target search/acquisition area (35 sq. km) offered by the hypersonic missile versus that offered by a more conventional Mn 2 missile (550 sq. km). Under the scenario described in Figure 3, the hypersonic missile will require approximately 4 minutes to reach the target while the Mn 2 missile will require 15-20 minutes, a time line which would be too late to prevent launch of the TBM and would likely be too late to locate the TBM launch vehicle as well, hence, the much larger target search/acquisition area attendant with the slower Mn 2 missile. Early interception is especially interesting to counter the proliferation of 2nd or 3rd generations of TBMs with multiple warheads (e.g. multiple chemical warheads), and with rustic or sophisticated decoys. Early interception of an enemy TBM during its ascent phase, although very difficult, can also prevent fallout of dangerous warhead products over the friendly zone of operation. Again, early inter-

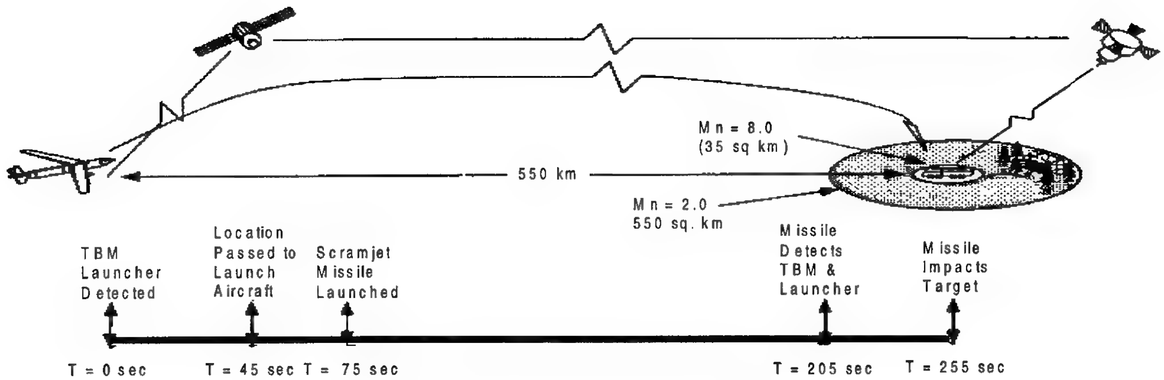

Figure 3 Scramjet Missile Mission Profile

ception during a TBM's ascent phase, requires early launch, preferably pre-launch target detection.

POSSIBLE MISSION REQUIREMENTS

A Mach 8 hypersonic air breathing vehicle could fulfill several mission requirements including:

* Extended Air Defense: A HABM could be a devastating weapon against extremely high payoff aerial targets. Such a target set in the future might include JSTARS, the airborne laser, AWACs, etc.

* Reconnaissance: The ability to provide potential target area assessments, at or near real time, can be a distinct advantage for a battlefield commander. A high speed vehicle configured with a specialized sensor and instrumentation suite becomes an attractive reconnaissance vehicle for use during peace time and against potential threats. For most nations, hypersonic reconnaissance missions would require the vehicle to return to base or, at least, to line-of-sight with a friendly ground station in order to download information. On the other hand, nations with access to space based relays would not have this limitation.

* Strike Against Hardened or Buried Targets: The sheer kinetic energy of a Mach 6-8 missile system makes it uniquely suited for this mission. However, deep or hard, point targets will require terminal seekers given the low Circular Error Probable (CEP) needed to defeat these targets. Furthermore, targeting data must be precise enough to allow a transition from Navigation Satellite System (NSS) or Inertial Navigation System (INS) navigation to terminal guidance.

* Strike Against Time-Critical Targets: Targets that may require rapid response include Tactical Ballistic Missiles (TBMs), aircraft, ground maneuver units, artillery, and ships. Some of these targets, in particular relocatable TBM's, may be situated hundreds of miles inside hostile territory and may evade detection by mobility and countermeasures. Therefore, the targeting data must be timely enough so that weapon launch can occur within seconds-to-minutes of target detection. The data must be accurate enough to allow weapons equipped with NSS receivers and INSs to achieve high probabilities of kill. Additionally, moving targets will require either in-flight targeting updates, or a seeker using Automatic Target Recognition for target detection and terminal guidance.

* Space Access: A Mach 6-8 hypersonic vehicle could provide a potentially affordable means of accessing space with small payloads.

At Mach 6-8, the hypersonic missile flies too fast to be shot down by existing methods. Additionally, it would take the development of extremely high performance exoatmospheric antimissile systems to threaten it. Consequently, the hypersonic system can virtually operate with impunity over enemy airspace and as such would be an affordable and cost effective weapon for the NATO war fighter.

CRITICAL DESIGN CONSIDERATIONS

A number of important weapon system design issues must be considered in order to bring to reality this technology push capability. These are highlighted below. An expanded description of the key technology development requirements for a fast reaction scramjet-propelled missile operating with a storable hydrocarbon

fuel is provided in the Requirements Section of this study report.

Vehicle Aerodynamics

The airframe and engine design must be highly integrated. At high flight Mach number operation, the HABM forebody is generally used as a compression ramp while the afterbody plays a role in engine exhaust flow expansion and thrust generation, and therefore in the net thrust produced by the scramjet engine. A high lift/drag ratio aerodynamic-configured vehicle, such as the "Waverider" concept, may provide the best basic vehicle concept in terms of range capability.

Air Inlet

The vehicle air inlet is an important component of a scramjet engine; in particular, inlet aerodynamic flow losses must be avoided or minimized. However, the main challenge for an affordable air-breathing missile operating over a wide Mach number range is to limit the variability of the air inlet geometry during subsonic launch, transonic/supersonic acceleration and hypersonic cruise. Movable parts designed to sustain inherent high mechanical and thermal loads tend to be complex, costly and heavy in weight, and therefore should be avoided. Additionally, an isolator duct between the inlet and combustor may also be necessary to prevent inlet unstart caused by combustor pressure influences on inlet flow stability.

Combustion System

For the scramjet engine combustion chamber, the following important technologies must be considered: fuel injection concepts, ignition devices, combustion kinetics enhancement concepts, mixture enhancement devices, wall cooling techniques, and afterbody design concepts. All of these design technologies must be integrated into the overall scramjet combustion system. Additionally, for effective control of the combustion process in supersonic flows, the fuel must be introduced to the flow field at various axial locations along the combustion chamber as a function of acceleration and cruise Mach number.

Structure

Due to the severe operating environment of the scramjet-propelled missile during flight and the importance of low weight on overall system performance, use of new high strength, high temperature and light weight materials will be needed. This could include application of ceramic matrix composites and coated carbon-carbon materials currently under development.

Fuel

In order for the HABM system to be a viable weapon with minimally required logistics support, sometimes referred to as having a "wooden round" capability, the system would require an easily storable fuel -- a fuel that can remain on-board the missile for very long periods of time, even years. This could be either a solid or liquid fuel. For this missile system, a solid propellant would be used for the missile booster while the fuel of choice for the scramjet propelled fast reaction missile would be a storable liquid hydrocarbon-based fuel possessing high heat sink endothermic properties. Such a fuel can serve a dual function -- supporting both thermal protection and combustion. For the thermal protection function, the fuel can be heated and decomposed by temperature via an endothermic reaction process, thus offering a cooling capability for the hot parts of both the air vehicle and the engine; hence, an endothermic hydrocarbon fuel can offer a significant advantage for this type of propulsion concept. The resulting total or partially gaseous decomposition products of the fuel are then injected into the combustion chamber and burned in the supersonic flow field. The main issue is energy management -- how to effectively control the fuel flow to the combustor in order to cope with both vehicle/engine structural cooling and combustion.

Booster

The scramjet engine will not operate at low flight Mach numbers (subsonic and low super- sonic); hence, a rocket booster is required to accelerate the vehicle to Mach 3 (dual-mode ramjet/scramjet) or to Mach 5.5 (pure scramjet) to ensure entrance conditions to the combustion chamber which will sustain combustion operation. The principal issues then become integration between the booster and the scramjet combustion chamber and transition between the booster phase and scramjet phase of operation. The preferred solution for the booster design would then be based on the technology offered by either a solid or liquid rocket booster concept.

Target Detection, Guidance and Tracking

High speed interception of fast moving targets requires accurate guidance and high maneuverability, especially in the terminal phase of target acquisition. An on-board Navigation Satellite System (NSS) will likely be an integral part of the vehicle guidance

system. Use of an auxiliary propulsion concept (e.g. lateral control thrusters) might also be considered, or perhaps a combination of both aerodynamic and auxiliary propulsion control during missile end-game operation may be required. It is recognized that target detection, guidance and tracking by the missile is largely dependent upon the specific target to be acquired and destroyed. The missile will require different equipment for different targets. For immobile targets, a precision navigation system will be required, but probably no specialized seekers and trackers will be necessary. On the other hand, for mobile targets, just the opposite will be required. For purposes of this study report, the specifics of terminal guidance and fusing are not addressed.

FURTHER CONSIDERATIONS

Related R&D Activity

A number of synergistic and related R&D activities will support and/or complement this advanced weapon system capability -- CFD for supersonic reactive flows; advanced propulsion simulation systems; advanced cost modeling for configuration selection including manufacturability and maintainability; enhanced test facility capabilities and "virtual wind tunnel" capability which closely couples test and analysis facilities at remote sites worldwide; high response and high temperature non-intrusive instrumentation improvements.

Weapon System Test and Evaluation

An effective Test and Evaluation (T&E) approach for hypersonic missile development within the next 10-15 years depends upon a well-defined methodology built on a baseline of existing or moderately upgraded ground test facilities, diagnostics and computational capabilities. This methodology must employ test, diagnostics and computation/simulation in a building block fashion geared to resolving key technical issues and reducing uncertainties. Existing ground test facilities will accommodate many component-level test requirements for a Mach 8 missile, and therefore provide computational verification at the component level. System level requirements are not well provided for, however, in terms of both ground test capabilities and linkage to flight test.

Propulsion/Airframe Integration

Critical design issues in scramjet propulsion and airframe/engine integration will drive development of computational and simulation capability, non-intrusive diagnostics, and facility upgrades in terms of scale, test medium, and test conditions. Full scale ground tests of the propulsion system with run times on the same order as flight are considered critical, combined with early risk reduction flight tests on a host platform; both capabilities require development.

Thermal Management, Structures, and Materials

Basic aerothermal test capabilities and methodologies exist for subscale testing. However, the strong coupling between airframe, engine, and cooling system design require augmenting aerothermal testing with a full scale capability which accommodates propulsion and active cooling systems.

Guidance System, Stability, and Control

Evaluation of missile stability, control system and guidance performance are strongly dependent upon accurate computational prediction of aerodynamic and propulsive performance verified through testing. A likely approach includes both subscale and full scale ground testing, supplemented by a separation and control flight test. Hardware-in-the-loop testing of the integrated seeker/guidance/flight control systems will incorporate the results of component and subsystem tests and computations in an iterative manner, yielding a buildup to full system simulation.

Weapon System Affordability

Depending upon the weapon system capabilities required, the hypersonic missile technology development, demonstration and evaluation costs have been estimated to range from $500-1000M. The average unit production cost today for a hypersonic missile system has been estimated at $1-1.5M per unit; however, by taking full advantage of technology that has already been developed, it is believed that both development time and cost could be substantially reduced. Affordability is further enhanced by keeping hypersonic missile costs competitive with that of current cruise missiles.

The application of scramjet propulsion to hypersonic missile weapon systems offers improvements in responsiveness, survivability and affordability. Such a weapon, when launched from current tactical aircraft, bombers, and/or ships, could strike targets 1200-1500 kms away in a matter of minutes with minimal collateral damage. Survivability, without the requirement for stealth, is enhanced by keeping the launch aircraft away from the heavily defended target area and by the near invulnerability offered by the hypersonic

speed of the Mach 8 missile -- a distinctive and important issue in terms of weapon system cost and affordability. This is not to imply that stealth related countermeasures may be unnecessary for a Mach 8 missile. For example, should an airborne laser weapon be developed some day, even the hypersonic missile may require stealth provisions and reflective surfaces

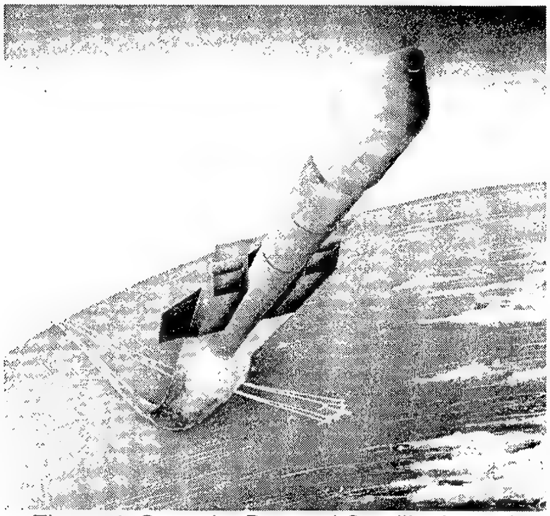

Figure 4 Scramjet Boosted Satellite Launch

as added survivability countermeasures. Additionally, fewer bases of operation would be required because of the increased lethality offered by the hypersonic missile system and by allowing a single launch aircraft to cover a footprint which would otherwise require numerous aircraft today.

Non-Defense Use

Satellite Launch Support: A typical scramjet satellite launch vehicle is illustrated in Figure 4, based on the Orbital Sciences "Pegasus" launch system. Current Pegasus systems are purely rocket propelled and because of high launch weight limitations must be launched from specially configured B-52 and L-1011 aircraft. Application of an air breathing scramjet system to replace the second stage rocket would nearly double available payload capability and permit vehicle launching from virtually any B-52 aircraft. Hence, non-defense use of this advanced air breathing propulsion capability could be particularly attractive as a low earth orbit satellite launch system. On the other hand, the cost and operational advantages of an air breathing propulsion system for a small satellite space launcher still may not be as affordable as the current fully rocket launched and propelled system. The basic concept, however, continues to attract interest and one day could perhaps become a cost effective and affordable solution to low earth orbit satellite launching.

International Cooperation

International cooperation will be both necessary and desirable in order to achieve this advanced weapon system capability -- US/Germany/France/UK. Additionally, non-NATO nations such as Japan and Russia could become possible participants as well – considerable high speed research is already underway in both of these nations.

Proliferation Risk

The risk of proliferation of this technology is considered to be moderate; the technology is complex and highly sophisticated and requires long term development and flight validation. It should be noted, however, that Russia is aggressively pursuing development of this technology capability (Figure 5), and if successful, would likely consider export of such a weapon system to international markets, including third-world nations. Figure 5 shows the Russian Scramjet Flying Laboratory, a scramjet engine mounted to the nose of a rocket booster. This is strictly a "captive-carry" vehicle to determine scramjet engine performance under actual flight conditions.

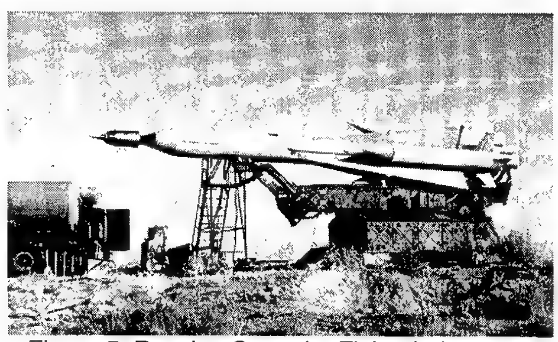

Figure 5 Russian Scramjet Flying Laboratory

KEY TECHNOLOGY DEVELOPMENT REQUIREMENTS

The following material expands on the technical areas of importance highlighted in the Executive Summary. This section has been divided into ten basic areas which define the critical design and/or operability issues and concerns that must be considered in order to bring the HABM to reality. Each area addresses relevant issues/concerns and briefly describes the current state-of-the-art and the known technical deficiencies/ shortcomings.

AIRFRAME/ENGINE INTEGRATION

For a HABM using storable hydrocarbon fueled scramjet propulsion, integration of the airframe and the scramjet engine is perhaps one of the most critical elements of the weapon system design. It is critical because the vehicle forebody becomes part of the air compression process of the engine, while the aft portion of the vehicle becomes part of the nozzle expansion process. As a result, proper engine/airframe integration is key to providing a low vehicle drag characteristic during high Mach number flight operation. This, when coupled with the inherent structural and weight requirements of the weapon system, causes the airframe/engine integration issues to be critical elements in the overall weapon system design. Further more, the application of unconventional seeker shapes and sensor windows for the missile system guidance package must also be considered as part of the airframe/engine aerodynamic and structural design.

PROPULSION SYSTEM

The key to a high speed (Mach 6 - 8) air breathing propulsion vehicle using storable hydrocarbon fuels is the scramjet engine. One propulsion system design approach would utilize a separate rocket booster for accelerating the vehicle to Mach 3 - 4, at which time the air breathing engine would begin to operate in a subsonic combustion ramjet mode. As the vehicle continues to accelerate to Mach 5 - 6 under ramjet operation, it would smoothly transition into the supersonic combustion or scramjet mode where it would operate during Mach 7 - 8 cruise. An alternative approach would be to utilize a larger rocket booster to accelerate the missile to scramjet takeover flight speed of approximately Mach 5. The rocket booster could be a tandem system which would separate from the scramjet vehicle after booster burnout, although it also be an integral part of the scramjet engine. In a missile system where flow path variable geometry would be too heavy and complex, simple two-position devices could be utilized for starting the inlet, or perhaps consumable structures could provide a temporary nozzle throat for improved ramjet operation during the acceleration phase. The forebody of the vehicle would provide some external compression for the inlet. The engine most likely would utilize endothermic fuels which could provide more regenerative cooling capability than conventional hydrocarbon fuels. Being able to cool the engine at the equivalence ratios required for cruise operation will in all probability also set the upper flight Mach number limit of the missile system. Hence, the key propulsion issues for the HABM are engine operability at low flight Mach number and engine performance and survivability at high flight Mach number.

Cycle Optimization

Cycle optimization for an HABM must include the integration aspects of the inlet, combustor and nozzle as well as the effect of the low Mach number acceleration process. In a scramjet engine there is strong interaction between the inlet/combustor and combustor/nozzle; hence, one cannot look just at the best individual components and assume that they will provide the best performing engine. For example, one very important design parameter deals with the amount of compression done by the inlet. If compression is too low, the pressure in the combustor will be inadequate for efficient combustion. If compression is too high, recombination losses in the nozzle will become prohibitive. In addition, the scramjet missile must be able to operate over a range of Mach numbers; consequently, limited variable geometry or, if possible, fixed geometry components are desired. Therefore, cycle optimization should not focus on each sub-cycle or component of the system, but rather on the global system. Optimum vehicle design can then be focused on vehicle forebody design, and on the definition of an appropriate low Mach number accelerator or booster.

Inlet/Combustor Interaction

The shock wave/boundary layer interactions, which occur in the region of the inlet terminal shock system for operating conditions of high relative heat release (high fuel-air equivalence ratios) in supersonic combustion, are critical in determining the inlet maximum total pressure recovery and in defining supercritical stability margins. If too much heat is released without sufficient stability margin, the inlet

may "unstart" resulting in a sudden loss of engine performance and dangerously high levels of pressure in the combustor. Inlet/combustor interaction is governed by fuel distribution and mixing in the combustor entrance area and by the corresponding internal area distribution. Many investigators are convinced that a long isolator duct is necessary in order to separate the intake exit flow from the influence of combustor pressure rise. Isolator duct length, however, is a controversial issue. For example, allowing for some internal pressure limitations, an engine designed with a short isolator duct may be a superior design in terms of overall integrated engine performance. Further work in this area will be required to assure an optimum inlet/combustor design.

Combustion Technology

The efficient combustion of a hydrocarbon fuel in a high speed air vehicle must consider all aspects of on-board fuel storage, fuel feed, fuel injection, fuel-air mixing, reaction chemistry, heat transfer, flow physics and combustion. Perhaps the most critical issues are the incorporation of proper fuel injection, fuel-air mixing, and fuel-air ignition techniques for optimum combustion within limited residence times. An additional problem may be the combustor configuration constraints resulting from the integration of the low Mach number booster acceleration engine.

An alternative combustion concept would be to use high heat sink hydrocarbon fuels which can be decomposed via an endothermic process resulting in gaseous fuel products that are then injected into the combustor. Research and development of high energy endothermic fuels has been underway for several years within the USA; the combustion kinetics and reaction chemistry associated with the basic endothermic conversion process are well understood.

Relative to future work in this area, a critical development issue which must be addressed is the aspect of hydrocarbon fuel and air mixing in high speed supersonic flows, essential for efficient combustion. Further, the influence of scale on the mixing processes should be investigated in depth.

Lastly, a large experimental data base was developed for hydrogen under the National Aerospace Plane (NASP) program as well as specific analytical CFD codes using hydrogen-air kinetics. Similar data and CFD codes will also be required for storable hydrocarbon fuels, since most hydrocarbons have large ignition delay times and greater reaction times than does hydrogen, and thus will be inherently more difficult to burn.

Two Phase Flow

Most hydrocarbon fuels are stored as a liquid in the missile; hence, the possibility exists for injecting a combination of both liquid and gas into the combustor. In that the liquid fuel will be used to cool the hot parts of the engine, some of the fuel will vaporize as it cools the vehicle and engine hot parts prior to its injection into the combustor. The injection characteristics of either a pure gas or a liquid into a supersonic flow is reasonably well understood; however, little data exists for injection of a mixture of both liquid and gas (two-phase flow). Existing CFD codes cannot currently handle the injection of two-phase flows into a supersonic stream.

Engine Operability

As flight Mach number is reduced, so is total temperature and flow Mach number of the air entering the scramjet combustor. With a reduction in total temperature, autoignition of the fuel and air within the combustor may no longer occur; hence, some form of pilot and/or flame holding may be required. As entering combustor flow Mach number is reduced, the amount of heat release by the combustor will be limited before thermal choking occurs, or before pre-compression shocks are forced into the inlet, resulting in possible flow separation and inlet unstart. However, this is also an operating regime where a high combustion equivalence ratio for accelerating the missile to the cruise Mach number is required. Therefore to reduce the amount of booster engine mass required for missile launch and initial acceleration, it is mandatory that the operational range of the air-breather to take-over acceleration Mach number be as low as possible. It should be investigated as to whether the minimum Mach number operational limit can be reduced to perhaps Mach 4.5 or less. Alternatively, research should be performed on dual-mode subsonic/ supersonic combustion, with special emphasis on combustion mode transition and its attendant performance penalties, and on system global performance.

Thermal Protection (Passive & Active)

Thermal integrity of the air vehicle and engine during high Mach number flight operation is a priority consideration. Passive thermal protection such as ablative materials, while adequate for typical flight times at Mn << 5 or for very short missions above Mn

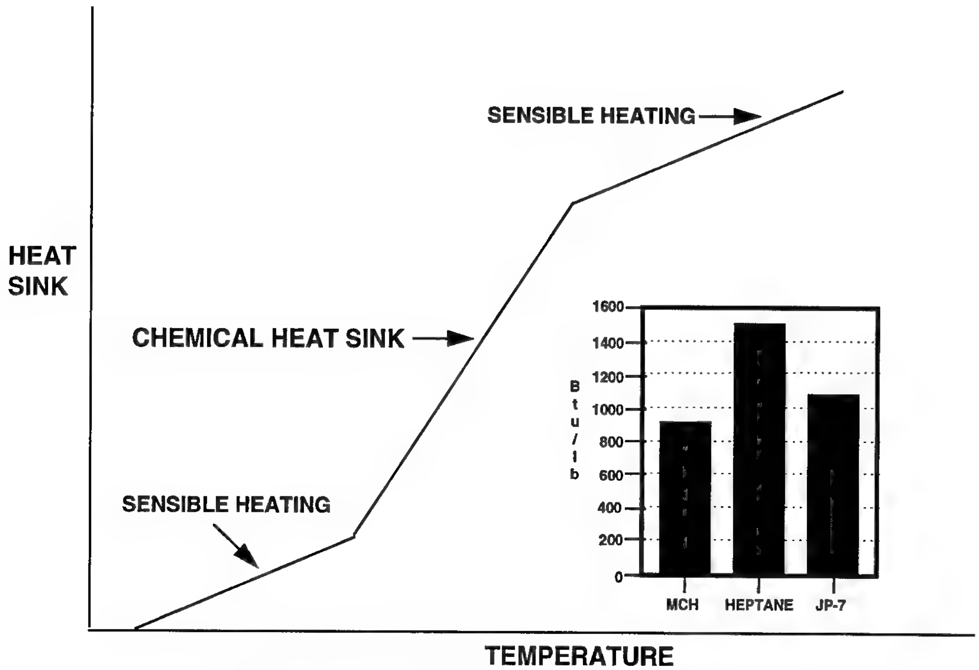

Figure 6 Endothermic Fuel Heat Sink Potential

= 6.5, may not be suitable for inlet surfaces -- due to potential critical geometry changes as the thermal protection surface material ablates away. For longer missions at high Mn > 6.5, the combustor and portions of the exhaust nozzle will require active cooling. Critical high heat load areas such as the fuel injection plane and regions where strong shock patterns are formed will also require special thermal protection consideration. However, for an affordable missile system, the associated complexity and cost of actively cooled structures must be limited as much as possible. As a result, the effective realization of high heat load, thermal-tolerant uncooled structures for high speed missiles may depend very heavily on the successful development of advanced high-temperature, high-strength composite materials having excellent oxidation resistance.

Endothermic/High Heat Sink Fuels

Active cooling will likely be required for high Mach number scramjet missiles (Mn >6.5) designed for operational flight times of moderate duration (>5-10 minutes). Endothermic fuels can significantly extend the limited thermal capacity of conventional hydrocarbon fuels by absorbing heat while cracking these fuels into lighter molecular weight hydrocarbon gases and hydrogen. In addition to the added cooling capability offered by the fuel, the products of the decomposition process are easier to burn than the original fuel. Considerable research into the understanding, development, and application of endothermic fuels has been underway over the past 20 years. Figure 6 shows a relative comparison of the heat sink potential of three classical endothermic fuels: Methyl-Cyclo-Hexane (MCH), heptane and JP-7. In principle, endothermic/high heat sink fuels provide the following advantages when considered for high Mach air vehicle applications:

* The increased cooling capacity offered by an endothermic fuel will permit active cooling of critical engine components and airframe/inlet forebody structures at fuel temperatures well above that allowed by a conventional hydrocarbon fuel.

* The vaporized or gaseous fuel products resulting from decomposition of the liquid hydrocarbon fuel, which can include hydrogen, greatly improves the fuel-air reaction time during fuel injection into the combustion system, and hence permits supersonic combustion of a storable liquid fuel required by engine designs of limited length.

On the other hand, the disadvantage of these enhanced heat sink, easier-to-burn fuel products is their inherently reduced fuel specific gravity -- which can lead to reduced range potential. Additionally, the need for active cooling will add a degree of complexity to the vehicle and combustion system design. Hence, a careful analysis of the thermal management issues relative to hot parts cooling will be necessary.

Actively Cooled Panels/Integrated Structures

Engine components subjected to severe thermal loads will require the incorporation of heat resistant materials and/or active cooling. Actively cooled structures may be a design alternative to the use of high temperature ceramic or coated carbon-carbon materials. This question is most critical with respect to structural weight, complexity and cost. As indicated above, the application of actively cooled structures demands the use of endothermic/high heat sink fuels as the cooling means of choice.

High Temperature Lubes and Seals

If variable geometry must be incorporated into the engine design (inlet/exhaust nozzle) in order to meet required system performance, a simplified, affordable engine configuration must be defined which can utilize two-dimensional, two-position variable geometry components. To protect the attendant seals and sealing surfaces from hot gas leakage, a thermal barrier of protective cold gas (of sufficient pressure) may be necessary. Hence, technologies for providing the necessary high temperature lubricant and thermal barrier protection systems must be developed.

Nozzle Chemistry/Kinetics/Performance

As flight Mach number increases, losses in the nozzle caused by flow divergence, friction and recombination become a dominate effect on overall engine performance. Recombination losses depend upon the finite rate kinetics of the specific chemistry of the hydrocarbon fuel being used. Theoretical non-equilibrium nozzle flow investigations typically focus on either a detailed modeling of chemistry/reaction kinetics, neglecting 3D fluid dynamic effects, or on detailed fluid modeling using a reduced thermo-chemical approach. As a result, deviations from experimental results may be encountered. Due to the highly nonequilibrium effects encountered in high speed nozzle flows, both experimental and theoretical work should be brought together as closely as possible in order to achieve optimal nozzle designs and performance.

Launch/Acceleration Booster

The scramjet engine will not operate at low flight Mach numbers; hence, a booster is required to accelerate the vehicle to Mach 3 - 4 (dual-mode ramjet/scramjet) or to Mach 5 - 6 (pure scramjet) to ensure entrance conditions to the combustion chamber which will sustain combustion operation. The principal issues then become proper integration of the booster and the scramjet combustion chamber, and propulsion mode transition between the booster phase and scramjet. The preferred solution for the booster design may be driven by the technology requirements and capabilities of either a solid or a liquid rocket booster. However, if missile launch and acceleration is to be accomplished using a solid rocket booster, the following known limitations must be considered:

* The scramjet combustor may be volume limited and, hence, may not be well suited for a design which integrates the solid booster propellant into the combustor flowpath. Additionally, the required booster propellant mass fraction may be unacceptably high for the integrated combustor/booster design in order to assure vehicle acceleration to minimum ramjet/scramjet transition Mach number.

* The application of a tandem or parallel rocket booster must also be considered. The possibility of employing a booster system consisting of both a tandem booster for initial missile acceleration followed by an integrated booster grain for final acceleration to scramjet transition should also be investigated.

THERMAL MANAGEMENT

Effective management of the thermal environment generated by the engine and airframe of a high speed missile system during flight must be handled in an integrated global fashion -- the principal task of satisfying the total cooling and thermal energy requirements of the system, within the limits of the resources available to that system. For high speed flight, engine/airframe thermal management is the proper control of thermal energy which will provide acceptable structural, material and component temperatures throughout the entire flight. Coolant distribution systems (active cooling systems), passive thermal protection systems (insulation, ablatives, high temperature materials, radiation cooling), and thermal/power transfer devices (heat exchangers, pumps) for all relevant airframe and propulsion system components, subsystems, and structures are included in the overall integrated vehicle thermal management system. Specific issues relative to thermal management of the weapon system include the following:

* Total vehicle active cooling requirements must match engine fuel flow requirements. If more active cooling is needed, fuel flow in excess of that required for combustion will be necessary, resulting in possible substantive vehicle range or speed degradation.

* Weapon system payload and guidance/target acquisition equipment compartments must be temperature controlled to ensure proper operation throughout the flight of the vehicle.

* As indicated above, critical scramjet engine component areas may also require active cooling.

* Should vehicle infrared signature for a hypersonic missile become an issue, special thermal protection and active cooling of the air frame may also be necessary. Complexity and cost inherent with an active cooling system, however, may become prohibitive in terms of ultimate weapon system affordability. Generally, the speed of such a missile (Mach 6-8) is considered sufficient to eliminate the need for controlling the infrared signature of the system during flight.

STRUCTURES AND MATERIALS

Hypersonic vehicles operating at speeds up to Mach 8 represent an extraordinary challenge for structures and materials. The airframe and engines require lightweight, high temperature materials and structural configurations that can withstand the severe conditions of the hypersonic environment. These conditions include very high temperatures, widespread heating of the whole vehicle, additional localized heating from shock waves that sweep across the vehicle during flight maneuvers, high aerodynamic and acoustic loads, severe flutter, vibration and thermally induced stresses, and material erosion caused by the airflow across and through the engines. The engine itself represents a particularly challenging problem because of the severe environment in the flowpath involving high thermal, mechanical and acoustic loading. As discussed earlier, in the engine and probably parts of the airframe as well, it may be necessary to control surface temperatures using the fuel to actively cool the various components for Mn > 6.5.

Over the last decade, significant improvements have been made in the development of lightweight, high temperature materials through programs underway in several of the NATO member countries. However, it is obvious that we still face many technical challenges in attempting to satisfy all the structural needs of a hypersonic vehicle. The types of structural materials used for near- and mid-term applications probably will include nickel, iron and cobalt-based superalloys, advanced refractory alloys, intermetallics, intermetallic composites reinforced with ceramic fibers, ceramic and carbon-carbon composites, and lightweight thermal insulation materials. In addition, for actively cooled structures in both the engines and the airframe, high thermal conductivity materials will be needed, along with materials or coatings that can survive contact with the hot fuel used for cooling. Most of these materials will require coatings to provide protection against oxidation and the other environmental conditions associated with atmospheric high speed flight. Furthermore, advanced processing methods will be needed to produce the necessary lightweight structures that in some cases may contain arrays of coolant passages through which fuel will flow as it controls the temperature of the structure. Along with the development of the materials and structures themselves, structural life prediction modeling, aerothermo-elasticity/loads validation and structural life integrity methodology will be key to the successful use of the advanced materials and structures. The following briefly highlights a number of critical issues/ concerns that will require close attention in order to meet the necessary materials and structural requirements for a high-Mach (6 - 8) air breathing vehicle.

High Temperature Metals and Alloys

The high temperature metals and alloys of interest for hypersonic airframe and engine applications include titanium alloys, titanium alloy composites, titanium intermetallics, nickel-, cobalt- and iron-based super-alloys, refractory metals and alloys, and copper-based alloys and composites. This is not an exhaustive list but it includes the primary classes of metallic-based materials that would be suitable for higher temperature applications in the engine and airframe. Much work has already been accomplished on these materials for potential hypersonic vehicle application and many of these materials have been extensively evaluated in the appropriate environments. For airframe applications, their use would be feasible in the relatively near term. For applications in the flowpath of a scramjet engine, however, further work is still needed to mature these materials before they could be applied with confidence. This also includes the need to design and build actively cooled structures that can withstand the fuel- and oxygen-rich high temperature conditions in the flowpath. Additionally, more accurate modeling and prediction of the thermal and acoustic environments occurring in and around the engine is needed.

Carbon-Carbon and Ceramic-Matrix Composites

Carbon-carbon and ceramic-matrix composites have the potential for use as lightweight structures exposed to very high temperatures without the need for active cooling. Because of their inherent high

temperature capability, they are regarded as candidates for use on the airframe as thermal protection panels located over the load-bearing substructure. They may also be used in a similar way in the inlet or nozzle of the engine. Much work has been done on these materials over a number of years and many practical applications have been found. However, in the case of carbon-carbon composites, effective coating schemes must still be developed to prevent catastrophic oxidation in the flight environment. Ceramic composites, on the other hand, have better inherent oxidation resistance. For both classes of materials it will be necessary to develop methods that will allow them to survive the hypersonic environment for the required weapon system mission time. Additionally, as with all composite materials, life prediction methodology must be developed and applied to allow confident prediction of their behavior on the vehicle.

High Temperature Sensor Aperture Materials

For control and navigation of hypersonic vehicles, it is necessary to transmit signals through windows or apertures that are transparent to the frequencies of interest. Materials that work well at lower speeds may not perform adequately at the high temperatures seen by the skin of a hypersonic vehicle in flight. Several classes of aperture materials have been developed for high temperature applications in ballistic missiles; however, the conditions on a hypersonic vehicle that can cruise for a relatively long duration (5-15 minutes) through the atmosphere may require modifications and/or upgrades of existing materials, or perhaps the development of new window/aperture material systems.

Nose Cap/Leading Edge Materials Development

Hypersonic vehicle nose and leading edge materials are exposed to the most severe kinetic heating. For efficient aerodynamic performance, leading edge radii must be very small, resulting in high loading, both thermally and mechanically. Shock impingement can also lead to local heat transfer rates greater than an order of magnitude for stagnation point heat transfer. Hence, materials with sufficient temperature resistance and thermal shock capability must be developed. Alternatively, leading edge designs that might incorporate active cooling should also be considered.

Manufacturing Technology for Regeneratively Cooled Structures

As discussed above, many areas of a hypersonic vehicle -- particularly in the engine -- may require actively cooled (fuel cooled) structural materials. This will be necessary in order to maintain material temperatures at levels that are within their capability. The actively cooled structures must be light in weight and must contain fine arrays of cooling passages located beneath the skin of the structure. These passages will vary in cross section from place to place throughout the structure and will be arranged in complex configurations in order to attain maximum cooling ability. The manufacture of these cooled structures will also require significant developments in fabrication methods. These methods will include diffusion bonding, brazing, and other approaches that can lead to the needed structural configurations.

Design Criteria Development and Validation

The use of hot, load-bearing structures on the airframe and in the engine of a hypersonic vehicle requires the development and validation of appropriate thermostructural design methods that have the capability to cope with the complex conditions that will be experienced during flight. These design methods and predictive models must account for a variety of effects not seen in lower speed flight, including the static and dynamic thermal, acoustic and aerodynamic loads generated as the air and fuel move at hypersonic speeds across the skin and through the engines. They must also address the particularly difficult problem of the severe effects of moving, intersecting shock fronts that can cause very high thermal and mechanical loading in localized areas. In addition, the heating caused by discontinuities in the flow path, such as gaps between panels, fuel injectors, support struts, etc., represents a very difficult challenge for available modeling and prediction methods. In general, while current methods provide a basis for designing hypersonic engines and vehicles, they cannot fully predict all the conditions that would be experienced in flight through the atmosphere for long mission times at speeds above Mach 4, and in particular, cannot define the full set of detailed conditions inside the scramjet engine. The development of suitable design methodologies is crucial to the successful use of materials and structures in a safe, reliable, affordable manner, as is the validation of design methods in realistic test environments that can simulate the extreme conditions of hypersonic flight.

COMPUTATIONAL ANALYSIS/DESIGN CODE DEVELOPMENT

The effective development and application of critical design codes and analysis tools are key to the successful development of a Mach 6-8 missile using a storable hydrocarbon-fueled scramjet propulsion

system. In that the scramjet engine is an integral part of the weapon system, vehicle external aerodynamics, the air intake system and the exhaust system must be well understood in order to optimize propulsion system performance capability and minimize vehicle drag losses throughout the flight envelope. Hence, the ability to analytically describe the air vehicle and propulsion system is critical to meeting the design requirements and mission goals of such a missile system.

CFD Improvements

Many Computational Fluid Dynamic (CFD) codes exist for the analysis of hydrogen-fueled scramjet engines. What is needed for the hydrocarbon-fueled scramjet engine is hydrocarbon kinetics models, to include the possibility of two-phase flows. Current kinetics models consist of several hundred reaction equations, all of which must be solved numerically. It is unlikely that complete reaction sets will be practical for use in 3-D CFD calculations due to the excessive computer time required; however, a simplified set of reactions along with their rate constants should be developed and validated for CFD use. Existing computational codes which are commercially available suffer from a lack of correct aerothermodynamic modeling. Highly nonequilibrium flows cannot be represented with most of these codes. Furthermore, they are not able to accurately represent regions of mixed flow (i.e. subsonic, transonic, and supersonic) which are typical in dual mode ramjet/scramjet engines, including interactions between the supersonic free stream and the local near-wall subsonic/recirculating flowfield. Additionally, the upstream influence of pressure rise within the scramjet combustor cannot be adequately modeled. Therefore, it is necessary to provide, within the near future, commercially available advanced computational design and analysis tools which are capable of performing these tasks based on reliable validation data obtained from well-defined experiments. In addition, it is essential that these computational design and analysis tools be integrated into advanced simulation systems capable of modeling the entire propulsion system, including component interactions at multiple levels of fidelity from one dimensional to three dimensional. These simulation systems are required to evaluate multiple propulsion system concepts and to enable a concept downselect process to a fewer number of optimized systems which would then be designed and tested. This simulation capability would also enable significant reduction in the time and cost of designing, developing, and testing the hypersonic propulsion system, essential for an affordable system development program. Work is currently underway to develop general architectures and critical communication and management links, but much more work is required. Work in developing the models that capture complex shock interaction fluid dynamics and combustion physics as well as the much higher degree of interaction among components in the hypersonic propulsion system, particularly between inlet/combustor and combustor/nozzle elements, is required. Multidisciplinary integration and optimization techniques need to be developed and incorporated into these simulation systems in a computationally efficient and modular fashion to enable multiple organizations to incorporate specialized and perhaps proprietary analysis and design codes into the system simulation methodology.

Turbulence Modeling (Compressible Flows)

Turbulence modeling is perhaps the most uncertain topic of fluid dynamics still under development. For example, the well-known k-ε model must not be used for highly compressible flows which occur with high speed aerodynamic flowfields or within chemically reactive flows, unless it is modified to account for compressibility effects. Other models compensate for this insufficiency, but are only applicable to a narrow band of problems. Even newer developments have not been promising. It is well known that tremendous differences exist between high speed laminar and turbulent flows. These must be properly modeled in order to effectively apply CFD as a performance prediction and design analysis tool for high speed air breathing propulsion. Consequently, turbulence modeling should be regarded as the most important issue within the context of CFD. Additionally, extended experimental and theoretical research is strongly recommended in order to provide more reliable theoretical models and/or experimental/semi-empirical correlations. Further, experimental validation of these models and analysis codes in realistic supersonic combustor designs is required.

Inlet-Shock/Boundary Layer Interaction/ Transition/Prediction

The effect of shock wave/boundary layer interaction on engine inlet performance is of great importance for HABMs. Inlet-shock/boundary layer interactions include reflected shock interactions, corner-flow shock interactions and oblique shock reflections, including separation effects. One of the most critical airframe/ engine configuration issues is the necessity to design an inlet of limited length, but with an oblique shock structure which can exceed the reflected shock wave separation limits by a considerable extent. Inlet com-

pression is typically accomplished with a long external compression forebody followed by an inlet cowl which generates an internal shock field. As a result, the highly viscous boundary layer entering the inlet will be subject to strong pressure gradients, and at some point may separate. Consequently, the effects of shock-boundary layer interaction in the vicinity of an expansion corner is an area of particular concern and requires fundamental investigation. Another special question is whether a series of oblique shocks can be tolerated without causing an inlet unstart. State-of-the-art experiments can be accomplished in either short duration experiments using cold structures (but where heat transfer is not represented correctly), or with quasi-stationary small scale testing (but where total temperatures and Reynolds numbers are not adequately simulated). To overcome the aforementioned deficiencies, flight testing of adequately instrumented engines of sufficient scale is required in order to effectively validate computational predictions.

In order to optimize vehicle flight performance, a sound understanding of shock boundary layer interaction and boundary layer transition and separation must also be known. It is important that design analysis tools and codes be developed which can accurately predict the flow field characteristics around the forebody and scramjet engine inlet in terms of boundary layer transition, separation and shock field interaction. Today, the prediction of boundary layer transition is done by linear and non-linear stability analysis using simplified flow models. The results obtained are promising when applied to flat plate boundary layer flows with or without downstream pressure gradients and adiabatic walls. These simplified flow models, however, are unacceptable when dealing with complex geometries. Furthermore, due to the mathematical complexity of the governing equations, there is no expectation that reasonable predictions can be made for the more complex flow systems. Even empirical results show considerable deviation for the same free stream Mach number, based on free flight testing and wind tunnel experiments. Consequently, the acquisition of good experimental data correlated with theoretical approximations from stability theory is essential for the designer's ability to understand and predict flow field boundary layer development, transition and separation.

Flow Diagnostics, Sensors

Within the supersonic flowfield, intrusive diagnostic measurement methods are not recommended because of their heavy influence on the main flowfield parameters and the severe thermal environment. Robust, non-intrusive laser-based diagnostics should be developed which can be applied not only to laboratory problems, but also to more complex and realistic engine geometries. For example, laser diagnostic measurement techniques should be developed in order to obtain full planar rather than single point only measurements for accurately characterizing high temperature flow fields. Additionally, integral quantity measurements related to engine performance should be developed; e.g., metric balances and metric strips. Non-intrusive temperature and pressure sensitive paints should also be further developed and applied to selected areas/components of the air vehicle.

Configuration Optimization

This issue focuses on the need for effective analysis and design codes which can provide design trades in order to arrive at an optimum vehicle configuration design suitable for the expected flight mission. Configuration optimization is a joint analysis effort which includes engine propulsion, vehicle aero-mechanics, and seeker/sensor dynamics. Both cost and weight implications can enter into this area in arriving at an optimized weapon system design. Furthermore, better models of cost estimation including manufacturability and maintainability are needed to ensure that the optimized configuration will result in an affordable, lower life cycle cost system. Since over 90% of the final cost of the propulsion system is determined in the preliminary design and configuration selection phase, it is essential that better tools are developed to estimate the total system cost during the early system decision phases. This is particularly challenging for new materials and highly integrated structures which require development of new manufacturing and maintenance processes. Finally, it is important that these models be developed concurrently with and are incorporated into the advanced simulation system discussed above.

Weapons Separation

In that a high speed air breathing missile system could be air launched, it is important to understand the aerodynamic loads the launch vehicle may impart to the missile during separation. Hence, the ability to effectively analyze the flow field around the missile during separation is very important. Furthermore, in the case of an air-launched vehicle, the classical external hanger array is by no means acceptable due to the local kinetic heating and severe drag increases inherent with hypersonic flight. Consequently, retractable hangers and plugs are mandatory for hypersonic vehicles.

WEAPON SYSTEM GUIDANCE AND TRACKING

In order for a HABM to be an effective and accurate weapon system, technologies in support of missile guidance, targeting, tracking, terminal or end-point accuracy, and mission simulation and testing are very important. At speeds of Mach 6-8, global positioning information of the weapon and the target are critical elements of the mission equation. Hence, the following critical issues/areas must be addressed.

Global Navigation Satellite System (GNSS)/ Inertial Navigation System (INS)

The performance of GNSS, particularly when integrated with inertial sensors, is not in general limited by platform velocity. The GNSS receiver and integration design, however, must take into account the platform's acceleration profile so that its dynamics do not exceed tracking loop bandwidth. This is routinely conducted for any integrated multi-sensor navigation system.

Targeting/Tracking Control System Logic

The operational utility of hypersonic weapons will depend directly upon the ability to provide accurate and timely targeting data to a variety of weapons delivery platforms. Targets that may require rapid response include the Tactical Ballistic Missile (TBM), aircraft, maneuvering units, long range artillery, multiple launch rockets, and missile boats/ships. Some of these targets, in particular relocatable TBMs, may be situated hundreds of miles inside hostile territory and may evade detection by mobility and countermeasures. Therefore, the use of Autonomous Target Recognition (ATR) techniques by long range, high speed, low observable unmanned air vehicles are critical. This targeting data must be timely enough so that weapon launch can occur within seconds-to-minutes of target detection. Also, it must be accurate enough to allow weapons equipped with GNSS receivers and INS to achieve high probability of kills against soft targets. Hard, point, or moving targets require terminal seekers given the low Circular Error Probable (CEP) in order to defeat these targets. However, the targeting data must still be precise enough to allow a transition from GNSS/INS navigation to terminal guidance. Hypersonic weapons with a terminal seeker may also use ATR for target detection, identification, and aimpoint selection without Man-in-the-Loop (MITL) operation. Additionally, moving targets will require hypersonic weapons which can receive in-flight targeting updates. Consequently, the targeting and tracking control system logic for a hypersonic weapon is a critical design issue requiring the effective integration of on-board sensors, receivers, and navigation techniques to permit a rapid response against a hostile target.

Lightweight High Energy Batteries

Electrical power for a high Mach missile system is a critical element of the weapon design. High energy batteries will be required to provide power for the guidance and control subsystems, the air vehicle control actuators, and the warhead arming and sensor systems. These batteries must be lightweight, high energy units capable of meeting all the power requirements of the weapon system for the duration of the mission. They must also be shock resistant and tolerant of the high thermal loads generated within the vehicle during flight.

Air Vehicle/Propulsion System Thermal Management Integration

As indicated earlier, thermal management throughout the entire high Mach weapon system is design issue of paramount importance with respect to missile guidance, targeting and tracking requirements. The on-board sensors and GNSS or INS receivers must be protected from the severe thermal environment generated by the vehicle during flight. On-board equipment compartments and warhead electronics must be maintained at a temperature level consistent with the operational limits of the electronic sensors contained therein.

Mission Simulation and Testing

Simulation plays an important role in the development and mission application of high speed vehicles. For the effective development of a high speed vehicle, simulation models are required to predict and to optimize the performance of the guidance and control subsystems. For this type of simulation, the models should represent highly accurate and detailed mathematical descriptions of the dynamics of the vehicle. This includes accurate data on the vehicle aerodynamics, propulsion system, sensors and control systems, as well as possibly complex mathematical expressions that must be evaluated by the simulation computer. These simulations are performed in a rather isolated way, in the sense that they are performed for individual vehicle developments. The simulations, therefore, do not have to fit in a wider hardware or simulation environment. Furthermore, computing time is not critical.

In the area of mission application of operational vehicles, simulation models are required to provide accurate data on overall weapon system performance in terms of speed, distance traveled, maneuverability and accuracy; however, these models may be less detailed as far as on-board subsystems, vehicle aerodynamics, sensors, guidance and control systems and propulsion systems are concerned. Such simulations may be performed to evaluate isolated missions for high speed weapon systems. However, these simulations will also, and preferably, be used in mission management systems. This implies that the simulation models must comply with interface requirements set by the management system environment.

The critical issue for both types of simulation methods described above is the accurate modeling of the air vehicle and its subsystems, in particular the propulsion system. Accurate aerodynamic data must be obtained by advanced computational fluid dynamics and experimental verification. Unfortunately, the propulsion system design is not fully available when development starts; consequently, a mathematical description of the propulsion system will be developed during the propulsion system design period. On the other hand, if this design information can be made available, the generation of the required simulation models should be fairly straight forward. This may in turn result in the development of the simulation models required for guidance and control system development as well as for mission simulation. Computer power to perform the necessary calculations is not expected to be a problem. Additionally, the expanded memory and computing speed required for simulation programs of this type are also progressing well and should not be a problem.

STABILITY AND CONTROL

For an air breathing missile accelerating to flight speeds of Mach 6-8, the ability to provide effective control and stability of the air vehicle is critical throughout the mission. Hence, the design of the flight vehicle control system and its ability to provide stable operation during the low speed, acceleration, and cruise points of the mission will require particular attention during weapon system design. For example, stability and control of the missile during flight can be strongly affected by airflow entry forces on the vehicle inlet system. Subtle changes in vehicle attitude and angle of attack can very seriously affect the stability and performance of the missile during flight. The flight control system will require powerful control surface actuators in order to overcome the aerodynamic loads encountered during high Mach flight. These actuators need to be compact, light-weight devices, perhaps electrically driven. Additionally, conventional flight control by the actuation of fins on a hypersonic vehicle can result in very high local heat transfer rates in the fin area. Therefore, the possibility of replacing the fin actuation system with a lateral side thruster attitude control system should be investigated. The potential for using ram-air for lateral side thrust pitch and yaw control should also be explored as a flight control system design alternative.

The direct measurement of the attitude (α,β) and velocity (Vo) of a vehicle flying at high speed using an anemo-baro-clinometric system can be difficult at high Mach numbers. Consequently, for vehicle navigation and engine control functions, it may be necessary to develop new technical solutions; e.g., laser-based velocimeters. Such measurement devices are already available at the laboratory level and have been applied to some helicopters and subsonic aircraft; application to hypersonic vehicles, however, must still be investigated. Additionally, the hypersonic vehicle guidance system must take into account new flight constraints, such as the effects of the propulsion system on the airframe. Hence, new control law methods must be investigated; for example:

- multiple targeting methods
- parametric optimization based methods using various optimization kernels; e.g., first order methods (projected or reduced gradient, ...) or second order methods (quasi-Newton,...)
- sensitivity matrix (or Γ-guidance) methods
- collocation methods

Additionally, in order to be compatible with real time computational constraints, one should also investigate parallel computing techniques from both the numerical analysis standpoint as well as the hardware and software architecture aspect. Relative to the vehicle control function, the principal challenges include:

- vehicle trim as a function of flight Mach number, on-board fuel load, vehicle center of gravity, etc., ...
- stability and control accuracy requirements relative to the trimmed vehicle angle of attack set-point
- control of fuel sloshing and vehicle structural bending modes

Of course, sensors, computers and control surface actuators required for vehicle guidance, navigation and control must be designed to withstand the severe

thermal environment generated within the vehicle during hypersonic flight. Again, the importance of engine/airframe thermal management becomes a critical design issue.

SENSORS AND SENSOR WINDOWS

The ability of a hypersonic missile system to effectively locate and destroy its designated target depends very heavily on the accuracy, sensitivity, and responsiveness of its sensor systems. Of particular interest is terminal or end-game sensor accuracy. In this regard, an all-weather terminal guidance sensor has a minimum operating wavelength of about 3 mm (W band) for acceptable atmospheric interactions. This leads to an angular resolution of 3/D (where D is the aperture diameter in mm). Terminal sensor accuracy may be improved (3 to 30 times) from this angular resolution value through signal processing, performing both target-to-background contrast enhancement (high range resolution, or Doppler analysis) and antenna processing (mono-pulse or others). Technology developments in these areas have shown promising capability improvements for low speed missiles or munitions. However, at hypersonic speeds, additional improvements to the sensor package design may be necessary. For example, the sensor window material must be able to sustain high temperature with limited dielectric modification; furthermore, window shape could produce high values of aberration directly limiting angular accuracy. An area of particular concern with hypersonic missiles is sensor window sensitivity and/or tolerance to possible plasma interference due to the formation of a plasma field over and around the sensor window itself. For a vehicle traveling at Mach 7-8, plasma production can form due to local heating by the nose shock and by ionization of possible ablated heat shield components (e.g., sodium, potassium, and other alkali-based ablative coatings) into the hot boundary layer over the sensor window. Plasma levels are generally a function of missile altitude, Mach number, vehicle shape, angle-of-attack, and heat shield purity. The ultimate impact of plasma formation at or near the sensor window is also a function of the sensor itself. The plasma can affect signal transmission through the window to the sensor such as RF propagation/attenuation plus phase shift, also antennae pattern perturbation, mutual coupling characteristics of antennae arrays, impedance match, etc. An on-board GNSS may be used for missile navigation/guidance; RF sensors are often used for missile guidance and homing during the terminal phase of operation; and communications links for positive control, command destruct, etc., may be appropriate using high frequency RF signals. All, however, can be affected by the possible formation of a plasma shield or blind spot over the sensor window. Hence, this potential sensitivity must be addressed during the design and development phase of the sensor/optics package and associated sensor windows. Sensor technology is yet another important area essential to the successful development and deployment of a HABM. The environmental conditions in and around the sensor electronic and optical systems as highlighted above can be critical to effective sensor operation and integrity. The sensing equipment must also be lightweight, robust, and thermally and vibration/shock insensitive.

AERODYNAMIC CONFIGURED VEHICLES -- WAVERIDERS

To obtain maximum range, it is important to have an aerodynamic vehicle with a high lift/drag ratio while at the same time producing a reasonably uniform flowfield for the scramjet propulsion system. Unconventional airframe shapes offer the most promising aerodynamic performance characteristics relative to lift/drag ratio for a hypersonic vehicle. For example, the Waverider concept can potentially provide the best performance in terms of range, and if designed with reasonable volumetric efficiency, can offer an attractive scramjet propelled vehicle design. Consequently, the Waverider vehicle design should be given serious developmental consideration for a hypersonic missile.

WEAPON SYSTEM TEST AND EVALUATION (T&E)

Key requirements for test and evaluation of a HABM exist in multiple design areas from the component to the integrated system level. Tests at all levels of design and integration must closely interface with computational modeling, both for prediction and verification of results. This necessitates a building block approach in which component level computational models provide performance predictions which are verified through testing. The resulting information is then used to predict subsystem performance which in turn is verified through an appropriate level of ground and/or flight tests. Testing, and its associated diagnostic tools, must be geared to reducing uncertainty and verifying computations at each level, including the integrated system level. The baseline for this methodology must be reasonably achievable in the near term, implying only moderate upgrades to existing test facilities and diagnostics, and minimizing the need for new dedicated test capabilities. Existing T&E capabilities may be adequate for certain

component and/or subscale evaluation of a hypersonic missile; however, improvements to both ground and flight T&E capability are required. Remote, real time coupling of computational analysis tools and advanced simulation systems to both ground and flight T&E facilities is also required to enable rapid assessment of the test results and real time test modifications. Current work has demonstrated the feasibility of using advanced communication satellites to transmit large amounts of data for a propulsion component with sufficient speed to remote sites enabling essentially "virtual wind tunnel" capability anywhere in the world. More work is needed, however, to demonstrate that this capability is feasible for a complex propulsion system. This capability would enable a new level of international cooperation to become a practical reality.

Propulsion

Uncertainties in engine operability, survivability, and performance in the hypersonic regime drive the need for full scale ground testing with run times on the same order as flight. Deficiencies exist in both scale and run time with current ground test facilities. The influence of scale on fuel mixing requires in-depth investigation. Characterizing the thermodynamic properties and chemical composition of the test medium, and its effect on propulsion, is critical and should be accomplished early on. Verification of combustor turbulence and fuel injection and mixing models is also critical. A test methodology involving the fuel control and active cooling systems must be developed. Booster/ramjet/scramjet mode transitions are critical, requiring specific facility operating conditions.

Airframe/Engine Integration

The strong coupling between inlet and engine performance in combination with the afterbody contribution necessitates a propulsion test facility which can accommodate an integrated inlet/engine/aft-body at full scale and at representative exhaust altitude conditions. Flight test of the airframe/engine subsystem may be a key risk reduction measure, requiring development of a host platform to achieve ignition and cruise conditions.

Thermal Management

Ground test facilities must accommodate propulsion system operation with active cooling mechanisms, including actual or representative fuel control and airframe cooling effects. At a missile scale, a fully integrated vehicle test may be feasible which would reduce risk in the areas of thermal management and propulsion operability and performance. Methods of simulating thermal "trajectories" consistent with expected mission profiles and operating scenarios are also necessary.

Structures and Materials

These test requirements are strongly tied to those of the propulsion and thermal management systems. Aerothermal test capabilities exist in high enthalpy arc facilities and aerothermal wind tunnels for subscale and limited full scale testing. Facilities must be able to approximate the thermal and acoustic environments during propulsion system operation. Critical flight-weight hardware must be evaluated under conditions comparable to those of early operability tests. In addition, aero-optic tests can be used to verify sensor window properties and capabilities under these conditions.

Stability and Control

Well established methods of integrated modeling, ground test and flight test should be applied to stability and control evaluations. Subscale wind tunnel tests and computational simulations may employ models equipped for multiple attitude control configurations, including lateral thrusters. Limited full scale stability tests during airframe/engine integration testing may be feasible, although facility modifications are probably required. Flight test of a "stability and control" test vehicle would help bridge the gap between propulsion flight tests and a full-up guided missile test, providing an airframe/autopilot evaluation through inflight separation and pre-programmed maneuvers.

Guidance and Tracking/Mission Simulation

Ground-based evaluations of the integrated sensor/navigation/guidance subsystems will be highly iterative as increasingly accurate aerodynamic and propulsion models are built. Hardware-in-the-loop testing will be central to design iteration and verification. Closed loop tests with navigation processing, mid-course guidance updates, and terminal seeker views are critical. Eventual flight tests of a complete missile system, including all guidance and navigation components, will provide mission verification in an operationally representative environment. These flights must be properly phased with preceding tests and simulations in order to effectively incorporate significant design changes, and they must be geared to supporting the mission simulation effort.

SUMMARY

Future air power will continue to require ever increasing flight speeds in order to acquire and engage a potential adversary in the most effective manner. Consequently, hypersonic weapons (both aircraft and missiles) which can use air breathing propulsion provide a very attractive and cost effective solution to the war fighters mission needs. The air breathing hypersonic tactical missile is made possible through the application of the Supersonic Combustion RAMJET, or SCRAMJET, as the propulsion system of choice. Recognized as the most promising air breathing propulsion technology for hypersonic flight speeds above Mach 5, it offers the NATO war fighter with a new capability for fulfilling critical missions of extended air defense, reconnaissance, threat suppression and space access, and at an economically viable cost. In particular, a scramjet propulsion concept which can take advantage of the high heat sink characteristics of a storable liquid endothermic hydrocarbon fuel offers considerable operational and performance potential at mission flight speeds to Mach 8. This report highlighted a number of critical technology development issues and needs which must be addressed in order to make this new weapon system capability a reality. The projected cost of development of this technology encourages, if not requires, a multi-national and cooperative effort. The end result, however, will be a tactical missile capability which offers improvements in responsiveness, survivability, and affordability. It can be ground, sea, or air launched with the capability of striking targets 1200-1500 kms away in a matter of minutes with minimal collateral damage. Furthermore, its high speed makes it nearly invulnerable and thus more survivable while its range potential provides a safe haven for the launch vehicle which can remain well away from heavily defended target areas. In conclusion, the successful development and fielding of this liquid hydrocarbon fueled HABM described herein, will ensure and significantly enhance NATO's air dominance position well into the next century.

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CHAPTER 2

THE FUTURE OF AIRCRAFT GAS TURBINE ENGINES

Richard J. Hill
Aero Propulsion & Power Directorate
Air Force Wright Laboratory
Author

ABSTRACT

Today it is well understood that low casualty battlefield victory is achieved through ***air dominance***. Air dominance is maintained by fielding affordable and durable high performance air platforms capable of delivering payload when and where needed by the field command. Key to successful air platforms is the propulsion system. Gas turbine engines have no equal in providing excess power for air platform maneuverability, armament control and mission flexibility at the lowest overall cost (production, maintenance, deployment, and fuel). The following report discusses the enabling research and development, both in progress and planned, that is providing the necessary low risk technologies to continue NATO's air dominance position through the next half century. These technologies will power attack, bomber, and cargo aircraft and rotorcraft; subsonic and supersonic missiles and unoccupied aerial vehicles of many new configurations.

INTRODUCTION

As we look well into the next century, there is still no foreseeable substitute for the fire power and mobility of aircraft and rotorcraft, and there is still no substitute on the horizon for gas turbine engines as the primary propulsion system. In addition, NATO is on the threshold of new weapon system capability enabled by advanced turbine engines--in the very near-term the technologies are in place for Advanced Short Take-Off/Vertical Landing (ASTOVL) and sustained supersonic cruise; and in the far-term the potential exists for advanced Unoccupied Aerial Vehicles (UAVs), global reach transports, global strike bombers, and rapid reaction fighters. In addition, excess engine power will enable future "electric" directed energy weapons and new non-hydraulic, non-mechanical aircraft control capability. Initial thinking of "future propulsion" started in the United States (US) with the Integrated High Performance Turbine Engine Technology (IHPTET) program. It was established in 1985 to be the first joint US Air Force, US Navy, US Army, DARPA, NASA, and industry program focused to develop turbine engine technologies for more affordable, more durable, higher performance propulsion engines. Major work by the entire US propulsion community made it happen. Due to its visionary planning, quantified goals, and significant broad-base payoff, IHPTET is now the model program for the world and is the keystone for future military and civil propulsion. Its merits are well understood. In the United Kingdom (UK) and France major effort is underway to formalize similar national programs. The UK's Advanced Core for Military Engines (ACME) and the UK/France effort for Advanced Military Engine Technology (AMET) are leading the way forward for Europe. In addition, in Europe, considerable advanced research focused on engine improvements is underway, to various degrees, by almost all other NATO nations. These nationalized programs are forming the springboard for propulsion advancements for NATO's airborne warfighters of the next century. NATO, with this new propulsion capability, will enjoy full air superiority in all emergency situations. The technologies discussed in this report are focused only on turbofan/turbojet and the turboprop/turboshaft engine types. All technologies, however, can be used for the entire spectrum of aircraft, rotorcraft and missile systems, as appropriate. The major difference for both turbofan/turbojet and turboprop/turboshaft engine technology when applied to unmanned or missile applications is in the area of cost and life limits versus system design limits. Hence, the technology once developed for man-rated applications can be "de-rated" and used in any non-man-rated mission dependent application. In addition, consideration is given to noise, NOx emissions, use of hazardous materials, and in general, "environmental friendliness" during development of all technologies. However, no specific discussion of environmental considerations is included in this report.

AIRCRAFT GAS TURBINE ENGINE IMPACT

The momentum of the current work on gas turbine propulsion technology must continue through the next few decades and concentrate on fully developing the emerging technologies if NATO is to achieve total success in the future. This technology will not only improve on our current capability; but, will ensure NATO's technical dominance in aerospace development. Through solidly investing in the

formulation of turbine engine innovative concepts, success will happen. These innovative concepts (technologies) are key to enabling future military aircraft capabilities and have significant impact on defense costs. The propulsion system (engine plus aircraft fuel) typically accounts for 40% to 60% of the take-off gross weight for both current and future aircraft (Figure 1) and about 20% to 40% of aircraft/weapon system Life Cycle Costs (LCC) -- development, production, maintenance, operations, and support costs). Accordingly, any increase in engine performance and reduction in engine costs, associated with established aggressive propulsion system goals, will be a major contributor to achieving significant gains in upgraded and future NATO air platforms. This major focus by the NATO turbine engine community will not only advance NATO aircraft superiority through high performance, affordable, robust engines, but will improve many aspects of commercial aviation. Up to 80% of all military propulsion is usable for civil aerospace, marine, industrial, or ground power industries.

The broad-base aircraft mission enhancing payoffs from this advanced NATO research are: major extensions in operational range; reductions in gross weight and acquisition costs for new aircraft; increased speed to intercept the enemy or reach the target faster; increased quantity of weapons brought to the target; overall platform improvements by closely integrating the rapidly advancing more electric propulsion systems and airframe electronic flight control systems; increased maneuverability; enhanced combat survivability through performance gains and improved low observable technologies; and an ASTOVL aircraft with greater range and payload capability than an equivalent size current fighter.

Examples of the benefits of technology application include the implementation of longer range, multi-mission fighter/attack aircraft such as the new F-22, F/A-18 E/F, the Eurofighter 2000, the Dassault Rafale, and the Joint Strike Fighter (JSF) which will allow one type of aircraft to conduct bombing operations while successfully defending itself against enemy aircraft. More fuel-efficient engines for helicopters and surveillance aircraft will allow them to conduct anti-tank and anti-submarine warfare operations for longer periods of time and at greater ranges. Long-range cruise missiles, laser-guided weapons and other type missiles will be used to attack hardened or heavily defended targets of high capital value with improved kill ratios and less collateral damage while reducing the exposure of aircraft and pilots. In a like manner, the role of UAVs will increase at a significant rate. They will fly the most dangerous missions, be able to stay

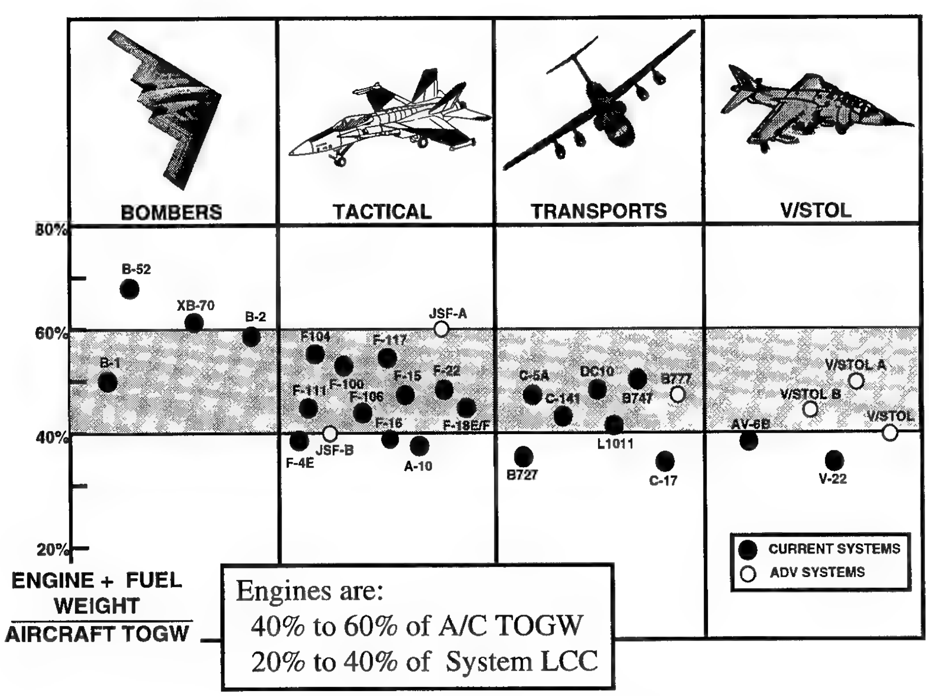

Figure 1. Turbine Engine Technology Impact

aloft for weeks or months at a time, and be inexpensive and durable. These UAVs will give the battlefield commander major options--options not yet fully realized in his advanced tactics and battlefield scenarios. All of this advanced aircraft capability will "fly" using the newly emerging, high performance, low cost gas turbine engine technology.

DEVELOPMENT OF GAS TURBINE ENGINE TECHNOLOGY NEEDS

Many major technical barriers must be successfully challenged for the payoffs discussed above to be achieved. These barriers include increasing component efficiencies; advancing structural integrity; increasing aerothermodynamic design capability (and control of heat transfer); improving combustion stability over a broad operating range with minimal emissions; developing high quality, low cost materials of lower density and greater high-temperature strength; maturing innovative structural design concepts; and ensuring compatibility of these developments with affordable manufacturing and repair processes.

A key ingredient of the technology development cycle to overcome these barriers is the utilization of bench, rig and full technology demonstrator engines where integrated component behavior is evaluated in a realistic environment. Through this proper testing, a high degree of technology readiness and transition potential will be understood and validated.

Currently gas turbine engines power the total variety of fighter/attack, heavy transport/patrol type aircraft and helicopters in addition to UAVs and several missile systems. Each of these weapon systems had to be developed with both a primary mission as well as other multi-role considerations that are integral to overall military operational plans. A prevailing issue with the gas turbine engine "cycle" is the need for increased power combined with lower fuel consumption. These are opposing requirements with respect to the thermodynamics of the cycle. In order to overcome this dichotomy, interactive subsystem design philosophies using the best technology are required in order to provide a "balanced performance" necessary to meet all aspects of the mission requirements. The process used by the gas turbine engine technology planners to meet all the aircraft roles is shown in the two step process of Figure 2. In step 1, the "warfighter's missions" drive the "performance requirements" which in turn set the "technology needs". In step 2, the technology needs that were defined in step 1 are developed into meaningful "technology goals". These goals are then evaluated for their contribution to achieving "performance payoff". These payoffs are then evaluated relative to what they provide the warfighter in terms of enhanced capability--usually much greater capability and more diverse capability than he first envisioned. Each of the technologies under development, for example in IHPTET and beyond IHPTET, has been chosen by application of this process.

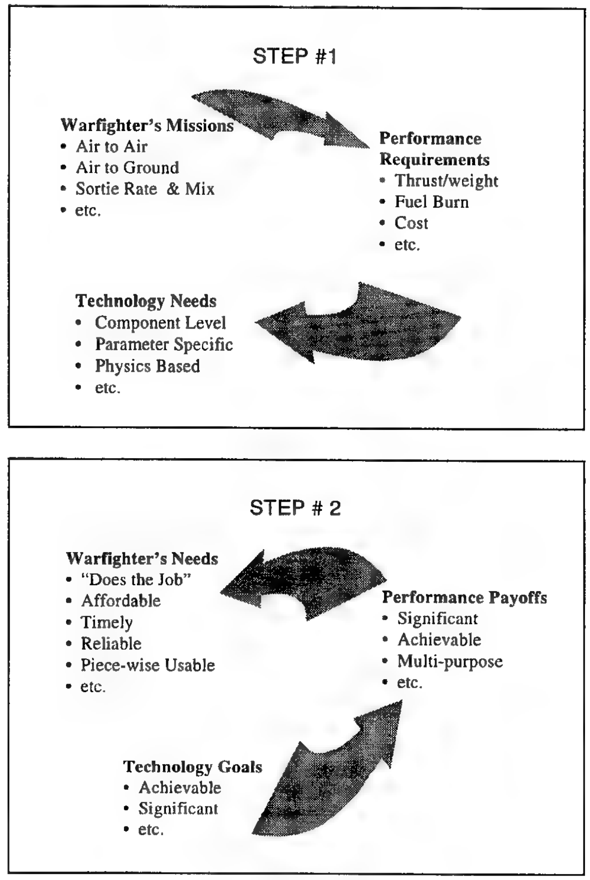

Figure 2. Propulsion System Technology Planning Process

Through the application of Figure 2, the path to this advanced, multipurpose propulsion system capability of the future is well described. It is well based in physics; but, will take high quality, focused effort to achieve. This path includes: higher temperatures at combustion initiation to increase thermal efficiency (or decrease specific fuel consumption) with expanded flight envelope performance; higher maximum temperatures to increase the thrust (work output) per unit airflow; and less weight per unit airflow to increase the work output per unit weight (thrust/weight or power/weight ratio); and all of these advancements must be accomplished with increased internal component efficiency, durability, and life, while decreasing cost.

Specific technology development areas include:

- Increased aerothermodynamic design capability for improved component efficiency levels and control of heat transfer
- Higher temperature and lower density materials
- Innovative structural concepts
- Robust designs that allow the engine to accommodate changing mission requirements while maintaining a high degree of readiness
- Durable designs and structures to provide full system life
- Maintainability concepts, such as modular construction and minimization of support equipment

All of these developments must be compatible with affordable manufacturing processes and accomplished in an integrated manner for each of the major component areas and for engine configurations as a whole. Advancements in total propulsion capability is a synergism of the three technology areas shown in Figure 3--success in one area alone will not do the job!

Today's (and tomorrow's) economic situation demands more affordable and durable propulsion systems. All aspects that impact the total system life cycle cost (LCC) can be improved with the successful application of advanced technologies. The technological range is very wide -- from enhanced computational fluid dynamics (CFD) techniques that enable designers to achieve the final design more rapidly, reduce the amount of "cut-and-try" testing and in general reduce the development time and cost; -- through improved manufacturing techniques to produce the systems; -- to the reduction in the number of parts, elimination of certain systems (for example, replacement of large portions of the lubrication system with magnetic or ceramic bearings), integrated diagnostic systems, and more fuel efficient power plants that reduce the operational and support costs.

For example, studies in the US's IHPTET program have quantified the weight and size influence on cost for a new engine in a fixed airframe and a new engine in a new airframe. Using IHPTET Phase II (planned 1997 demonstration date) technologies for example, studies show a 40% acquisition cost saving for a system with a constant aircraft thrust loading and fuel weight fraction equivalent to an F-16. Using Phase II technology to retrofit a new engine to a current airframe (new engine at same thrust) shows a 25% acquisition cost saving. The benefit of the technology on the engine size and weight is shown in Figure 4. Using IHPTET Phase II technologies individually or in small upgrade packages for modernization of current propulsion systems show proportionate values of LCC

Progress in All Three Areas Is Required for Success!

ADVANCED AERO/THERMAL +	NEW MATERIALS +	INNOVATIVE DESIGNS
◆ 3-D Viscous CFD Tools	◆ Lightweight Composites	◆ Fiber Reinforced Hardware
◆ Swept Airfoils	• Metal Matrix	• Ring Rotors
◆ Stoichiometric Combustors	• Carbon Based	• Blades
◆ Advanced Turbine Cooling	• Ceramic Matrix	• Static Structure
◆ High Stage Loading Compressors	◆ Ti & Ni Aluminides	◆ Multi-use Structure
	◆ High Temp Al & Ti	◆ Simplified Rotor Supports
◆ Short Exhaust Nozzles	◆ High Temp Non-structural	◆ Integral Blading
◆ Variable Cycle Concepts		◆ Laminated Structure
◆ Vaneless LP Turbines		◆ Endothermic Fuels
		◆ Magnetic Bearings

Figure 3. Propulsion Technology Triad

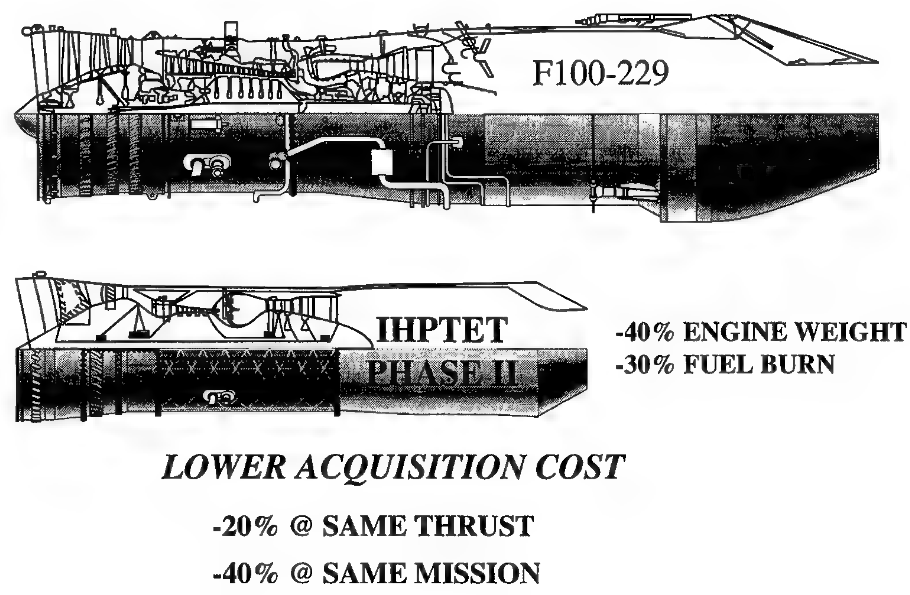

Figure 4. Revolutionary Advancement in Turbine engine Design

savings. Considering that the US Government spends approximately $15 billion per year on aircraft and missile gas turbine propulsion systems, a 25% to 40% acquisition cost saving amounts to a significant financial saving. For Phase III technologies (planned 2003 demonstration date) and "Beyond IHPTET" planning (2009 demonstration date), the payoffs increase to a 50% to 60 % cost saving.

In the future, each aircraft/rotorcraft will require an engine that satisfies a specific range of performance and cost goals. To meet these goals the engine manufacturers (or consortia/team) must determine what technologies are to be applied and how each technology is to be traded-off to maximize the effectiveness of the total weapon system. A fully equipped technology base with multi-use application is the key to successful propulsion system development and production. This concept is shown in Figures 5 and 6. Figure 5 shows the broad technical aspects of the "common core" technology base -- all currently in the engine technology development plans. Figure 6 shows the diverse capability that could be achieved with revolutionary turbine engine technology providing dramatic gains in range, reduction in mission time-to-target, and reaction time -- achievable through advancement in propulsion technology.

TURBOFAN/TURBOJET PROPULSION TECHNOLOGY NEEDS

The advanced strike aircraft and rapid reaction fighters, as shown in Figure 6, in general have certain system requirements:

- Multi-Mission Flexibility
- High Combat Maneuverability
- Dry Supersonic Operation
- Minimum Vehicle Size and Weight
- Low Fuel Burn
- Affordable Cost
- Easy Maintenance and Repair

The fighter aircraft shown in Figure 6 have common attributes that are satisfied by propulsion systems having many of the emerging technologies outlined in Figure 5. These fighter engines typically are mixed flow afterburning turbofan engines (bypass ratios of 0.2 to 1.0) which provide high vehicle airspeed (high thrust) and high values of "excess specific power"--the agility advantage. These engines are comprised of the technologies which, when focused, will achieve:

- High Thrust to Weight Ratio
- High Specific Thrust Cycle (Thrust/Airflow)

- Low Specific Weight (Weight/Airflow)
- Low Specific Fuel Consumption (Fuel Flow/Thrust)
- Low Life Cycle Cost--Total Cost of Ownership
- Increased Values of Signature Reduction

Fighter pilots are convinced that "speed is life, and life is speed". The higher speed is necessary for both ingress and egress to the battle area and the ability to quickly recover lost airspeed due to combat maneuvering.

Another benefit of higher thrust levels is improved payload capability which is very important for attack type aircraft as they apply ordnance-on-target. The major key to higher specific thrust is higher operating temperatures internal to the engine. Current combustor and turbine systems still operate well below the stoichiometric chemical limits of kerosene based fuels. In the future, major increases to these values will be required. For this to be achieved, new, high-temperature, nonmetallic materials are a major emphasis of new designs in the compression systems. In the hot section (Combustor, turbine, nozzle), advanced materials need to be integrated with thermal barrier coatings and innovative cooling techniques that require less cooling flow (a major "loss" factor in engine design) in order to be an effective improvement to the engine cycle. The other factor of the thrust/weight equation is lower engine weight. Again, new high-strength, low density nonmetallic materials and composites are being developed for all parts of the engine to produce light-weight parts. Cases, rotors, shafting and blades are all areas that are utilizing advanced material and design concepts. Fewer stages in the fan, compressor and turbine systems are major weight reduction initiatives that are made possible by improved component aerodynamic efficiencies and stronger materials. Compression systems that develop higher pressure ratios per stage, and turbines that extract more work per stage are all tremendous contributors to engine weight reduction. The development of new designs to better "master", mechanically, the thermodynamic behavior of the engine cycle (e.g., the Variable Cycle Engine (VCE) offers many advantages over the conventional "fixed" cycle). In order to exploit fully the advantages of the VCE, advancements in all areas of the triad of Figure 3 are required.

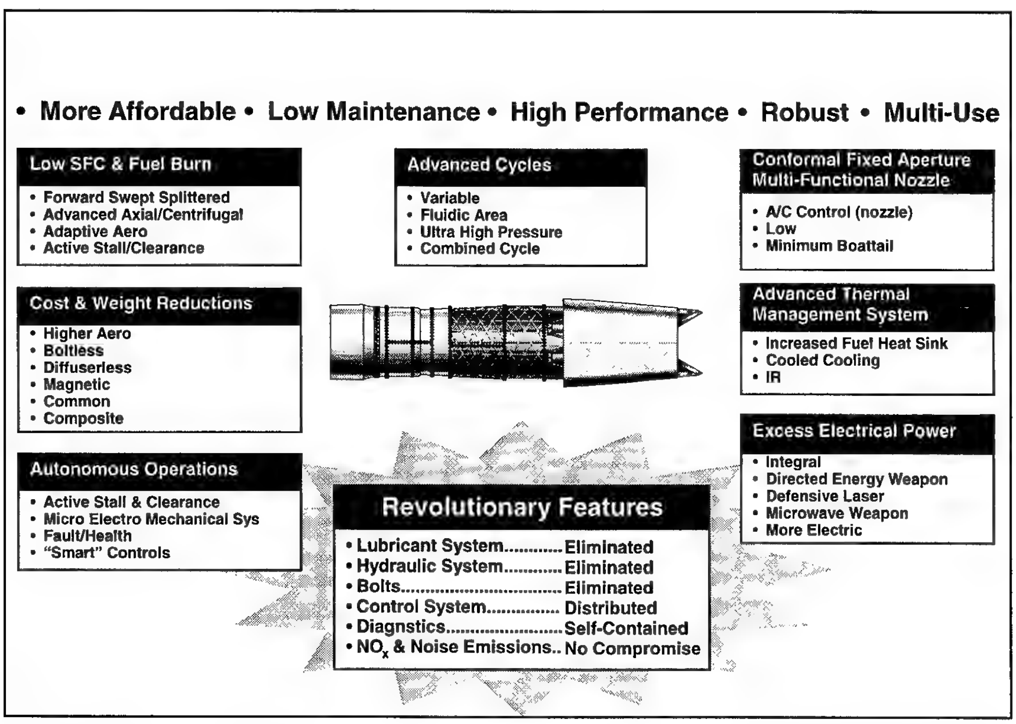

Figure 5. Emerging Advanced Technologies

The continuing development and availability of radar and missile systems to non-NATO countries pose increased threats to NATO aircraft. The incorporation of low observable technologies presents a substantial challenge to both the operators and maintainers of NATO aircraft. The role of the engine in achieving low aircraft signature is large. Engine designers must continually employ advanced technology as they try to increase the stealth effectiveness, reduce the weight and complexity of the propulsion inlet and exhaust systems, and improve the robustness of low signature surfaces. This area of advancement is fully dependent on the continuation of ongoing programs in the engine technology programs of the future.

A third aircraft of the future, as shown in Figure 6 as the "Global Reach Transport", needs an engine of high bypass ratio (BPR of 5.0 or above). High bypass ratio engines (in various thrust classes) are utilized for heavy transports, patrol/surveillance aircraft and long range cruise missiles and UAVs. The major issue of importance in these missions, in general, is low specific fuel consumption (SFC). Lower SFC provides improved range and time-on-station. The figure of merit to achieve low SFC is higher cycle pressure ratios combined with reduced weight. This is accomplished primarily through higher aerodynamic efficiencies in the fan and compressor engine sections in conjunction with a reduced number of compression stages. The higher efficiencies are achieved through the use of higher rotational speeds and application of advanced computational fluid dynamic (CFD) codes which permit the optimization of the flow through the compression section minimizing boundary layer losses and stagnation points. Other technologies include low aspect ratio wide-chord blading, leading edge sweep, casing treatments and mixed flow designs. In these types of compression systems, weight is reduced through the use of "blisk" construction (blade and disk as one unit), hollow blades, fewer stages and metal matrix composite materials. Improvements in engine control system capacity, sensor data "throughput" and response time are now allowing compression systems to operate more efficiently in off-design regimes and with lower stall margins. This translates to higher pressure ratios,

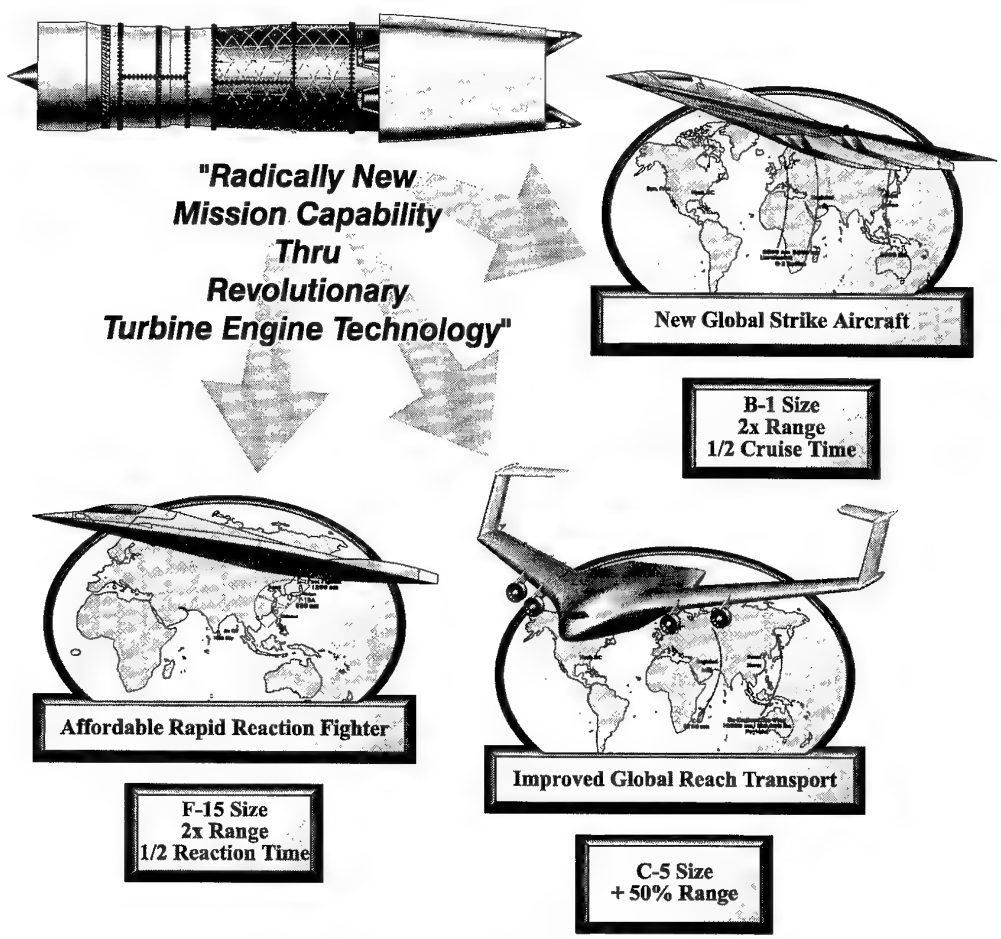

Figure 6. New Capabilities Through Advanced Propulsion

safely, throughout the flight envelope with lower weight.

For over 50 years, the gas turbine engine has used metallic alloys based in the nickel and titanium families. The properties of these material systems have been characterized and are well documented. Design standards and manufacturing techniques were developed with high confidence levels that high-quality hardware could be produced. The new, next generation of superalloys, intermetallics and nonmetallic systems is causing the gas turbine industries to establish new design standards, production processes and repair/inspection techniques before incorporating them into the next generation of gas turbines. With respect to these new advanced material developments, a whole host of new metallic and nonmetallic materials is being developed for specific uses in gas turbines. The environment in which these materials must operate is severe in terms of temperature levels and excursions, and dynamic stress fluctuations--the engine is murderous on materials! Therefore, extensive development and testing of new materials are required to reduce the risk to acceptable levels before being incorporated into such a complex system as the gas turbine engine. Metal, organic and ceramic matrix composites along with monolithic ceramics, titanium and nickel aluminides are all relatively new material systems that are being investigated for integration into many parts of the engine. Other major issues associated with incorporating these advanced materials are: the ability to manufacture with a high yield rate; maintainability (repairability); durability (life levels); and understanding and controlling failure (wear and fracture mechanisms) while in use by the warfighter. This knowledge is fully covered by work in the "materials" leg of the triad shown in Figure 3.

For both the fighter and transport aircraft engines, improvements in the thrust/weight ratio (fighter priority) and low specific fuel consumption (transport priority) goals can be generally characterized as benefiting from:

<u>Increased Propulsion System Thrust/Weight:</u>

- Higher Cycle Temperatures
- Improved Component Aerodynamic Efficiencies
- Advanced High Temperature Materials
- Advanced, High Strength, Low Density Materials

<u>Lower Specific Fuel Consumption:</u>

- Increased Pressure Ratio
- Improved Component Aerodynamic Efficiencies
- Reduced Cooling Flow and Leakage Flows
- Reduced Dry Pressure Loss for Augmented Engines
- In-flight Engine Performance Optimization

The advanced planning for propulsion has included all of the major engine component areas. Each area has specific time based goals to support overall engine system improvements. The magnitude and combination of these technology advances applied to specific designs vary depending upon the desires of the engine manufacturers and intended air vehicle system.

<u>Compression Systems:</u>

- Higher Aerodynamic Efficiency
- Improved Stage Loading
- Reduced Leakage
- Reduced Weight
- Higher Exit Temperature

<u>Combustor/Augmentor Systems:</u>

- Higher Inlet Temperature
- Higher Exit Temperature
- Reduced Weight
- Improved Turndown Ratio
- Reduced Dry Pressure Loss for Augmented Engines

<u>Turbine Systems:</u>

- Higher Operating Temperature
- Increased Work/Stage (Fewer Turbine Stages)
- Higher Efficiency
- Reduced Weight
- Reduced Cooling Flow

<u>Controls/Mechanical Systems:</u>

- Fiber-Optic Control Systems for Increased Data Throughput and Improved Electromagnetic Immunity
- On-line Performance Optimization
- Integrated Flight/Engine Controls
- Magnetic Bearings/Ceramic Bearings
- Increased Lubricant Temperature
- Advanced Sensors and Actuators

Exhaust Systems

- Fixed Area Designs (for Afterburning Engines)
- Fluidic Exit Area Control
- Thrust Vectoring
- Airframe-Exhaust Nozzle Integration

Materials:

- High Temperature Titanium Alloys
- Titanium Aluminides
- Nickel Aluminides
- Metal Matrix Composites
- Ceramic Matrix Composites
- Organic Matrix Composites
- Thermal Barrier Coatings

Environmental Requirements:

- Reduced NOx
- Reduced Unburned Hydrocarbons
- No visible Smoke Emissions

Developments in these areas will result in improved aircraft and weapon system performance combined with reduced maintenance events and lower acquisition and LCC. The development of integrated processes must be improved and shortened to reduce production costs and more rapidly take the product to the marketplace. These gains are also dependent upon advanced technologies, such as computer aided design and manufacturing methods.

TURBOPROP/TURBOSHAFT PROPULSION TECHNOLOGY NEEDS

Turboprop/turboshaft engines are used in a variety of utility, attack, UAV, cargo and surveillance aircraft. These applications include both fixed and rotary wing aircraft. These aircraft operate primarily at low altitude and cannot capitalize on the improved efficiency of operating at higher altitude. The recent Desert Storm experience revealed an operational need for increased payload and range for these aircraft, especially the rotary wing, and reemphasized the need for efficient inlet erosion protection systems and lower signatures. The primary technologies which will provide these increases are those which lead to improvement in engine specific fuel consumption (SFC) and power-to-weight ratio (Hp/Wt).

Technologies which lead to improvements in SFC and Hp/Wt include the following:

Reduced Engine SFC:

- Increased Pressure Ratio and Operating Speed
- Improved Component Aerodynamic Efficiencies
- Reduced Cooling Flow and Reduced Internal Leakage
- Engine Performance Optimization and Component Integration

Increased Propulsion System Hp/Wt:

- Higher Cycle Temperature
- Reduced Cooling Flow and Reduced Internal Leakage
- Improved Component Aerodynamic Efficiencies
- Advanced, Low Density, High Temperature Materials
- Advanced Inlet Protection Systems
- Increased Turbine Rotor Speed

The primary driver for increased range is reduced engine SFC. The cycle parameter which contributes most to reduced SFC is increased pressure ratio. The technologies critical to achieving increased pressure ratio along with improved efficiency are: application of advanced CFD codes to optimize flow and minimize losses along with advanced, high-strength, low density materials which will allow the higher tip speeds required for higher pressure ratio compressors. Other technologies which contribute include: advanced controls to allow performance optimization, advanced seals to minimize leakage and advanced bearings to accommodate the higher rotational speeds.

The primary driver for increased Hp/Wt is higher cycle temperature. The technologies critical to achieving higher cycle temperature are: advanced combustor designs to achieve higher exit temperatures while maintaining superior exit temperature distribution; the ability to operate smoothly over a broad range; advanced materials and cooling techniques to maintain structural life; advanced turbine designs with improved cooling techniques and advanced high temperature materials to maintain and/or improve turbine life with minimum cooling air penalty. Other technologies which contribute are advanced bearings and seals capable of operating at higher speeds and temperatures.

In terms of component technologies to support overall turboprop/turboshaft engine improvements, all of the major component areas have specific goals. They include:

Compression Systems:

- Higher Aerodynamic Efficiency
- Reduced Weight
- Higher Exit Temperature

Combustion Systems:

- Higher Inlet Temperature
- Higher Exit Temperature
- Reduced Weight
- Improved Turndown Ratio

Turbine Systems:

- Higher Operating Temperature
- Increased Work/Stage
- Higher Efficiency
- Reduced Weight
- Reduced Cooling Flow

Controls/Mechanical Systems:

- Fiber-Optic Control Systems for Higher Data Throughput and Improved Electromagnetic Immunity
- On-line Performance Optimization
- Integrated Engine/Flight Controls
- Magnetic Bearings/Ceramic Bearings
- Advanced Sensors and Actuators

Gearbox/Transmission Systems:

- Reduced Weight
- Compact Design Concepts
- Hydraulic Design Concepts

Materials:

- High Temperature Titanium Alloys
- Titanium Aluminides
- Nickel Aluminides
- Metal Matrix Composites
- Ceramic Matrix Composites
- Organic Matrix Composites
- Thermal Barrier Coatings

SUMMARY

Across the spectrum of NATO nations, propulsion plans and programs are in place to ensure that NATO's air superiority capability remains unaltered into the next century. The objectives are clear, the goals are achievable, and progress is being made. The turbine engine technologies emerging from the current programs will not only provide the necessary derivatives and growth of our currently fielded turbine engine systems; but also for the visionary systems for the future. In summary, the gas turbine engine presents many technical challenges, but the payoffs are worthy of sustained investment--without the engine, the aircraft becomes little more than a heavy glider. The propulsion technology development programs of IHPTET, ACME, and AMET are maturing the technology to power effectively and efficiently the future NATO aviation forces.

CHAPTER 3

FUTURE DIRECTIONS IN ROCKET PROPULSION

Mr. Lee Meyer
Rocket Propulsion Directorate
Air Force Phillips Laboratory
Author

ABSTRACT

The future trends in solid, liquid and hybrid (liquid oxidizer and solif fuel) rocket propulsion systems for space launch and tactical missiles are discussed in this chapter. The space launch area includes booster and orbit transfer propulsion. The tactical area included technology for ground, sea surface launch and air launched missiles. The propellants for tactical, in addition to conventional liquid and solid propellants, include gels. Spacecraft propulsion included liquid monopropellant and bipropellant, solar electric propulsion and solar thermal propulsion concepts. Advanced materials for high temperature liquid engine components: lightweight structural components: low erosion nozzle materials for solid rocket motors: high strength to weight materials for solid rocket motor cases are discussed. Controls and health management for specific applications are discussed to provide more capability for thrust vector control and engine health monitoring.

PROPELLANTS

Boost and Orbit Transfer Propulsion

Current Space Lifter propellant systems consist of solid or liquid propellants. Although these technologies can be viewed as "mature", cost reductions, environmental improvements and performance increases can be achieved by developing new ingredients, additives, formulations, improved processing, use of advanced high performance thermodynamic cycles and component design.

Solid Space Launch Propellants Due to the chemicals involved in solid propellant manufacturing, processing and firing, solid propellants will be constrained by an increasing number of environmental regulations by the year 2000. Programs to change the processes used in manufacturing and chemicals created during firing must be conducted to meet the regulatory challenge. In past efforts, performance has been sacrificed by replacement ingredients with less energy or lower density in order to meet the environmental restrictions. Development includes programs to reduce or replace ammonium perchlorate (AP) to eliminate the HCL in the exhaust, and programs to reduce or replace the aluminum powder as the fuel to decrease particulate emissions. The utilization of commercially available energetic, nonhalogenated oxidizers (ammonium nitrate and nitrate esters) are combined with high energy commercially available fuels and binders (e.g., magnesium aluminum alloys and polyether binders) to produce propellants capable of meeting these objectives.

Propellant developments to meet the solid propellant mechanical property objectives require an improved understanding and development capability of the internal mechanics of solid propellants (specifically binder-filler adhesion, particulate composite micromechanics, and fracture mechanics at the microstructural level). New binders and fillers also include finding corresponding bonding agents, catalysts, and additives that provide mechanical property control without compromising propellant performance. Approaches include improving and utilizing modeling and simulation technology to predict the mechanical and chemical properties of the propellants and guide the formulation and processing of new propellants and propellant mixes. The resulting enhanced simulation of the propellant mechanical properties will allow the attainment of higher mass fraction and structural reliability of the propellant grains in solid rocket motors at significantly reduced testing costs, and increased safety by eliminating the need to formulate dangerous propellant mixes until a solution is determined. Other cost reductions will be realized through decreased processing time by eliminating manufacturing steps or using continuous mix cycles.

Liquid Propellants Current state-of-the-art liquid systems are LOX/RP-1, LOX/LH2, and NTO/ Hydrazines. The storable systems utilize the toxic nitrogen tetroxide (NTO) oxidizer and hydrazine-based fuels. The LOX/RP-1 systems are less energetic than the

$LOX/LH2$ systems, but are significantly less expensive as well in some applications. Non-toxic storable propellants need to be developed to meet the environmental requirements in the future.

Spacecraft Propulsion

Future satellite maneuvering and on-orbit control requires improved reliability and operability to enhance satellite lifespan. Propellants are sought for selected missions which offer life cycle cost benefits through improved operability and/or reduced infrastructure requirements. Such propellants will be more benign and require less ground/flight support equipment than state-of-the-art, without significant sacrifice of mission performance. Liquid propellant improvements in density impulse will be accomplished with respect to bi-propellant storable and monopropellant storable systems. Non-toxic environmental approaches require assessments against program issues (such as system uses) in new programs. Programs to achieve these improvements include research into synthetic fuels and hydrogen propellants which can be tailored to operational requirements. Additional critical activities will be directed towards improved ignition and manufacturing capabilities.

Tactical Propulsion

Tactical Missiles: The wide-range of missions for tactical systems require multifaceted technology applications to address the higher performance needs with improved survivability, environmental compliance, at no comprimise to cost or safety. Increasing propellant energy for the under 10,000 lb-sec total impulse motors, 10,000 - 75,000 lb-sec total impulse motors, over 75,000 lb-sec total impulse motors, gun launched motors, and assist boost motors requires development and application of new propellant ingredients (for smoky, reduced smoke, and minimum smoke propellants). These ingredients (fuels, oxidizers, and binder systems) will have to be of higher heats of formation and/or higher density. Near term approaches include GAP, ADN, CL20, and perhaps metallic hydrides. Propellants will have to be formulated to eliminate current burn-rate and combustion stability problems at pressures above 3,000 psi, and with greater strength than currently available to allow higher volumetric loading. In addition, tactical systems will no longer be limited to solid propulsion concepts. Liquid and especially gel propellants will be investigated for possible use. Tactical missile propellants being developed must be able to meet the insensitive munitions requirements.

PROPELLANT MANAGEMENT DEVICES

Propellant Management Devices (PMD) technology area requires technology improvements in hardware cost, support cost, reliability, and reduced component weights. This will be done by reducing the component weight, increasing the component reliability, and decreasing the individual component cost. PMD hardware for liquid rocket engines represents 35-40% of the weight and 35%-40% of the cost of the entire liquid rocket engine system. This hardware includes: liquid propellant turbopump assemblies (including pumps, turbines, housings, ducts, connectors, and insulation), high pressure propellant and pressurant storage tanks (including expulsion hardware), and propellant tank pressurization systems. PMD hardware for solid rocket motors includes the motor case assemblies (both the case and insulation). The motor case and insulation are 43-70% of the motor inert weight and 25-30% of the cost. The PMD technology area will pursue innovative subcomponent and component design methods, manufacturing techniques, and materials appropriate for the respective component and application areas.

Boost and Orbit Transfer

Reusability has important implications in the design of liquid rocket engines demanding more severe life requirements for the turbines, pumps, bearings and dynamic seals compared to expendable engines. The primary technology challenges addressed in Phase I Boost and Orbit Transfer for liquid rocket engines are related to bearings, materials, flanges and connectors, and lines and ducting. The technological challenge for bearings is to survive a high rotational speed with little lubrication. Implementation of fluid film bearings requires resolving issues of compressibility of cryogenic hydrogen, transient wear conditions, and fault tolerance. The support of hot, high oxygen content, systems which are light weight and reliable requires materials development. Robust structural materials will be developed for oxygen compatibility and for use of non-metallic in subcomponents which typically only use metallics. To reduce assembly and replacement time, more easily operated, reliable, leak free connector designs and seal materials are also required. Development of high performance non-rubbing seals to separate incompatible fluids, e.g., liquid oxygen from hot hydrogen rich gases, is also an important issue for the turbopumps of future liquid rocket engines. New manufacturing processes, such as powder metallurgy, should be developed and qualified

to improve performance and reduce the cost of high rotational speed components.

Improvements in case and insulation materials will address the challenges of reducing solid rocket motor weight. For solid rocket motors the advancements that have the highest payoff are advancements of materials and a decrease in the variability of manufacturing. Improving insulation thermal performance per unit weight while the reducing the thickness required will result in system weight and performance improvements. Decreasing the variability of the forming process can also decrease the weight by the reduction of the safety factors or conversely increase the reliability by maintaining the safety factors while improving the manufacturing process.

Spacecraft Propulsion

The issues for reducing the weight and cost, and increasing the reliability of components for spacecraft propulsion deal mainly with small cryogenic tanks and insulation. Cryogenic propellants offer major performance gains for upper stage orbit transfer, but pose special challenges for satellite propulsion due to cryogenic storage problems. Novel ground support concepts are required which will enable the low cost management of cryogenic fluids during the loading and launch phases of the missions. In addition, lightweight, low boil-off, cryogenic propellants in-space storage concepts are essential to fully realize the performance potential of cryogenic propellants.

Tactical Propulsion

In tactical propulsion, the motor case is the primary inert component affecting mass fraction improvement capabilities (for motors without TVC). In all tactical applications higher strength to weight/ volume case materials are required for higher pressure operation and greater propellant loading at reduced weight. Weight constrained systems require high strength to weight materials and volume constrained systems require high strength to volume materials. Volume constrained systems tend to be less than 75,000 lb-sec total impulse (but these systems can also be weight constrained). The motors with less than 10,000 lb-sec total impulse are man portable systems with volume and weight constraints. These systems have very poor mass fractions and will gain the most from the improvements. Tactical motors in the 10000-750000 lb-sec total impulse, and over 75000 lb-sec total impulse, can all experience significant performance improvements with better internal insulation. Internal insulation with lower erosion, lower density, and lower heat conductivity will allow less insulation to be used and more propellant to be loaded into the motor. Significant performance gains are possible with integral rocket ramjets operating in both ramjet and booster modes. Motors with less than 10,000 lb-sec total impulse rarely have internal insulation and would not benefit from insulation improvements. The insulation materials, case materials, case construction and other components must be selected to meet the insensitive munitions requirements in order to produce a benign response to stimuli such as bullet impact, fuel fire, etc. Instrumented rocket motor cases will also become a practical proposition for in-service systems. These cases will make possible in-service data-logging of the propellant grains thermal and stress state history. This in turn will allow a much more informed appraisal of useful service life. Service users will wish to make use of this technology.

COMBUSTION AND ENERGY CONVERSION DEVICES

Combustion and energy conversion devices in the liquid chemical propulsion area includes the thrust chamber assembly (ignitor, injector, combustion chamber, and nozzle), and the gas generators or preburners. The major advances required in liquid propellant combustion devices include an increase in theoretical Specific Impulse (Isp) by increasing chamber pressure, increases in Isp efficiency as measured by Isp actual/Isp theoretical, reductions in weight, reductions in cost, and increases in reliability (measured by decrease in part count).

The solid propulsion area consists of nozzles and the ignitor. In solid propulsion the major advances required are in increasing Isp efficiency, decreasing component weight and volume, decreasing component cost, and increasing reliability.

Chemical spacecraft propulsion will require improved thrust chamber assemblies (similar to the improvements in boost and orbit transfer thrust chamber assemblies. Electric propulsion developments for satellites include the power processing components and the thrust chamber assembly, including the electrode. Major advances are needed in improving the power processing efficiency, the energy conversion efficiency, and combustion chamber life, and electrode life.

Boost and Orbit Transfer Propulsion

The thrust chamber assembly represents an average 32% of the overall cost of a boost or orbit transfer engine. Current manufacturing techniques employed rely heavily on expensive forging, machining, welding and brazing processes that require large amounts of touch labor. Development efforts should concentrate on the significant reductions in cost and component lead time that will be realized by incorporating advanced design and fabrication techniques into the next generation engine. Examples of this include the use of cast structural jackets to replace the current forged and welded structure, and diffusion bonding nonprecision cooling tubes to replace the brazing of precision stacked tubes. Injector costs can be reduced through lowering the number of injector elements, eliminating expensive welds and brazes, or through the use of advanced techniques such as laser drilling and platelet technology to manufacture injector elements. Solid rocket motor nozzle cost will be reduced by reducing the processing time and number of steps.

The thrust chamber assembly represents an average of 41% of the mass of a liquid rocket engine. In order to increase the thrust to weight ratio of the propulsion system this mass must be reduced. The usage of advanced composite materials to replace structural metal jacket should result in the largest weight reductions possible on the engine. Passive radiation cooled nozzle extensions further enhance the weight reductions through the use of lightweight composite materials. Reusability has important implications in the design of liquid rocket engines demanding more severe life requirements for the thrust chambers, nozzles, preburners and/or gas generators.

In order to achieve significant increases in liquid propulsion Isp the chamber pressure of a liquid rocket engine must be increased. Current materials are limited by a combination of temperature capability and thermal conductivity. Increases in either of these parameters will increase the pressure capability of the thrust chamber without the need for efficiency robbing propellant film cooling.

Current engine designs are optimized for maximum performance at only one specific altitude, hurting performance at all other altitudes. Delivered Isp can be improved by either improving the combustion (c*) efficiency of the combustion chamber or through the use of altitude compensation in the expansion nozzle. Current technology fixed bell nozzles are optimized for maximum performance at only one fixed altitude. Operation at any altitude other than the design point results in a performance loss. Altitude compensation, either through the use of translating, ventilated, or dual contoured bell, or "unconventional" concepts such as aerospike nozzles will allow liquid engines to operate at near optimum performance throughout the flight trajectory.

On solid rocket motor nozzles the delivered Isp can be improved by decreasing the nozzle throat's erosion rate. An increase in nozzle throat area creates an accompanying decrease in area ratio. This is counter productive to performance, especially in the case of space booster motors where an increase in area ratio with increasing altitude is desired. Composite materials with higher temperature capability and oxidation resistance are required to maintain throat geometry.

Improvements in c* efficiency will be sought for LOX/RP-1 engines through design improvements in the injector. Current efficiencies are from 90-94%. Improvements in vaporization and mixing will enable increases to the range of 96-98%. Combustion stability must be maintained with this increase in performance.

For the ignitor component of liquid engines, methods of increasing reliability and supportability will be developed. Current bi-propellant torch ignitors require individual propellant lines and associated valving to function.

Solid rocket motor ignitors are commonly initiated with electromechanical arm/fire devices requiring a complex explosive ordnance train. Electro-optic arm/fire devices which incorporate a laser diode through a fiber-optic transmission cable have the potential for lower weight, reduced cost and higher reliability.

Spacecraft Propulsion

In chemical systems for satellite propulsion the major challenges are cost, Isp efficiency, and volume. Because these systems are generally radiation cooled, Isp efficiency gains will be achieved through the development of higher temperature capable materials and new technologies. New techniques for applying coatings to extend the chambers temperature capability will be explored. Concepts to reduce the dimensions of satellite propulsion systems are also required for volume constrained satellites or launchers. High pressure pump (or pressure) fed systems may offer 50% volume reductions and improved performance. Cost savings will come from the same composite manufacturing techniques that apply to the space launch application components.

Satellite propulsion of nonchemical means includes electric propulsion, solar propulsion, and nuclear propulsion. In electric propulsion, the current technology is a specific impulse of 520 seconds, an energy conversion efficiency of about 33%, operating lifetime of 800 hours, and a power processing efficiency of approximately 90%. Improvements in arcjet systems are required in order to reduce mass, extend life, and reduce power requirements. Significant increases in satellite lifetime can be obtained by increasing the arcjet specific impulse and energy conversion efficiency. The approach to improving these parameters include the reduction of frozen flow losses and/or the reduction of power deposited into the arcjet body. The arc in the arcjet is notorious for squandering up to 50% of the input power into the non-recoverable internal energy modes (frozen-flow losses) of the propellant (e.g. ionization and dissociation). As service life of satellites are extended, so must the operational life of the arcjet. For high power arcjets, the major issue is the cathode life. Technology needs to be developed to extend the lifetime up to 2500 hours. Pulsed plasma thrusters, hall thrusters, and ion thrusters are other possible solutions to meet the increasing demands placed on satellites.

Hall type thrusters offer a performance advantage over Arcjet thrusters in some thrust classes. Development work on the components to reduce size and increase efficiency will be carried out.

Pulsed Plasma Thrusters are able to operate in thrust ranges below those other electric propulsion systems can operate. Component improvement programs will be run to improve performance and reduce weight and volume.

A new class of propulsion system is Solar Thermal Propulsion. Work needs to be accomplished in developing the concentrator and thrusters.

Tactical Propulsion

All tactical motors can benefit from reduced erosion nozzles. Incorporation of low cost carbon/carbon materials or refractory metals may have significant benefit. Tactical motors in the 10,000-75,000 lb-sec total impulse, over 75,000 lb-sec total impulse, assist boosters, and divert categories can be operated at altitudes from sea level to over 100,000 ft altitude. Altitude compensating nozzles (such as an aerospike) need to be developed to provide optimum expansion ratio at varying altitudes which can provide increases in delivered energy in excess of 3% add an additional 5% increase in motor performance. These nozzles must be designed to be minimum weight/volume systems to avoid loss in propellant loading when compared to current nozzle designs. Motors with less than 10,000 lb-sec impulse usually operate near sea level and thus altitude compensating nozzles would have little or no impact. There will also be a need for thermo-structural materials allowing simple low cost nozzle designs for tactical motors.

CONTROL SYSTEMS

Technology advances are required for control components to reduce propulsion system hardware cost, reduce support cost, increase thrust-to-weight, increase mass fraction and reduce failure rates. Application of innovative subcomponent and component materials, manufacturing processes, design methods and approaches appropriate for the respective component application area will be pursued.

Different types of application driven propulsion systems (liquid, solid, etc.) use vastly different control system components. Technology areas consists of the following components:

- Liquid engine health management (includes sensors, controllers, and control software).
- Valves and regulators
- Solid motor and liquid engine thrust vector control (TVC) actuators.
- Solid rocket hot gas valves

Boost and Orbit Transfer Propulsion

Decreasing the weight, power requirements and costs of liquid engine valves is achieved through reduced torque valve designs (making electrical mechanical actuation possible), incorporating advanced materials and low friction seat materials. Improvements in materials, processes and design techniques allow for the use of integrated multi-function valves.

Highly reliable propulsion system health management sensors and controllers are required for propulsion status monitoring and life cycle surveillance. Sensors of interest include flow, temperature, pressure, rotational speed, position sensors and accelerometers. Developing more reliable sensors with non-intrusive measuring techniques are desired. When intrusive methods can't be avoided, new sensor designs and fastening techniques will be developed (especially for reusable systems). Fault tolerant control logic with a minimum number of sensors required for prudent status monitoring is essential to guard against sensor failure induced engine shutdowns. Validation of optical and magnetic sensors being used for health management systems will also be completed. Furthermore, maintainability and health

monitoring become important aspects to be taken into account during design and development of a reusable system.

Similar to liquid engines, current TVC systems for solid rocket boosters are heavy and expensive. Electrohydraulic or pneumohydraulic systems are used where lower actuation forces are required. Current TVC actuators are large as well; they have historically been hydraulic due to the requirement for large actuator force, high slew rates and vector angles.

For solid motors the simplest TVC concept is the hot gas injection system where the combustion gases are bled from the combustion chamber and fed through a hot gas valve into the nozzle and exit cone to cause flow separation and effect thrust vector offset. The limitation for this concept has been materials capable of withstanding high combustion gas temperatures and combustion products.

Spacecraft Propulsion

Liquid propellants pose unique challenges for satellite propulsion systems. These propulsion systems, while required to operate for long lifetimes (over 10 years), must be highly reliable in addition to meeting restrictive weight goals. Frequently, component designs are compromised to meet the restrictions. For example, valves and regulators are being deleted from system designs in order to save weight (despite the seemingly trivial weight they add). This compromise is suspected of causing some satellite failures due to the lack of adequate propulsion system control. Satellites will also benefit from more reliable, fault tolerant health management systems similar to what is being developed for space launch propulsion applications.

Tactical Propulsion

For tactical propulsion, control systems need to include improvements in thrust vectoring, thrust modulation, and actuation technologies. These efforts must include capabilities to handle liquid and gel propellants as well as traditional solid propulsion pulse motors and thrust vectoring. Tactical gel and liquid propellant systems require low cost, low weight, low volume valves and regulators for propellant pressurization and feed systems. Chemical compatibility, sealing, and safety will be the primary problem in this research. Tactical motors in the 10,000-75,000 lb-sec total impulse, over 75,000 lb-sec total impulse, assist boosters, and divert categories will all experience significant performance improvements with better control systems technology. Improvements in the thrust vector control system include reductions in system mass by the development of high specific strength materials with good thermal and erosion resistance. Reductions in cost by using integrated low parts count designs using thermo-structural materials are required. Thrust modulation for solid propellant motors is a technology goal with particularly high systems benefits combining the ruggedness and low cost of solid systems with the flexibility of liquid propellant systems/

SUMMARY

In spite of many years of development of rocket propulsion technology, significant advances are still possible and can produce significant payoffs for a large array of weapon systems, space launchers and spacecraft. Improvements in thrust to weight of liquid engines, mass fraction of solid motors, improved reliability, increased performance and reduced cost all contribute to provide as much as a factor of two increase in the capability of space and tactical systems. Improvements in solar electric and solar thermal propulsion concepts can provide more than a four fold increase in capability compared to liquid systems currently in use. All of these improvements must be methodically matured to provide the confidence required for the user to incorporate them in new weapon systems.

CHAPTER 4

PULSE DETONATION WAVE ENGINE

Dr. Raymond Edelman
Boeing, Rocketdyne Division
Author

Robert E. Henderson
Universal Technology Corporation
Editor

ABSTRACT

Tactical missiles based on Pulse Detonation Wave Engines (PDEs) have the potential of increased range, enhanced survivability, lower cost, and reduced time of flight. The advantages derive from two overall features of the intermittent combustion device compared to competing steady flow engines. The first feature is the quasi-constant volume characteristic of the detonative combustion process with theoretical increases of the specific impulse and the thermodynamic cycle efficiency. The second feature is related to a simple design which combines compression, combustion, and thrust production in one component. The paper discusses various missile applications of the detonation based cycle, several design issues, and R&D needs which have to be resolved to take full advantage of the PDE.

VISION

Achieve a propulsion system with higher thrust and Isp at lower weight, smaller size and reduced cost relative to more conventional steady flow systems.

The pulse detonation wave engine is a device that can provide more than a 30% increase in thermodynamic cycle efficiency compared to the constant pressure burn Brayton cycle. Experimental work conducted over the past five years has focused on the viability of this engine concept, and the results indicate the potential of achieving high performance over a wide operating range. Airbreathing and rocket modes of operation are possible providing the capability to self boost and carry out subsonic and supersonic missions while changing modes on demand.

SCOPE

The current interest is in the development of the detonation wave engine derived from two overall features of this intermittent combustion device. The first feature involves the improved propulsive performance attributable to the quasi-constant volume characteristic of the detonative combustion process increasing the useful energy available for thrust production. this leads to a theoretical increase in Isp of up to a factor of two compared with a ramjet, depending on the application (speed, etc.). Furthermore, the increase in thermodynamic cycle efficiency associated with the high rate of heat release of the detonation process, on the order of several thousand feet per second, also indicated a thrust-to-crossectional area significantly higher than competing systems. The second major feature of the pulse detonation wave engine is its construction in which compression, combustion and thrust production occur mainly in the detonation (combustion) chamber. The two features lead to compact, lower weight (higher thrust-to-weight) designs that are potentially simpler in construction than competing steady flow engines. These advantages apply at all speeds, subsonic and supersonic.

MILITARY NEED

The improved range, survivability, low cost (simplicity), and potential reduced time of flight features associated with the superior performance

potential of pulse detonation wave engines, meet many military requirements for tactical missile systems. Consequently, a broad range of applications are possible using the full potential of this detonation based cycle. Table 1 summarizes a crossection of applications that include air launched, surface launched, Rocket Based Combined Cycle (RBCC), and pure rocket mode missions.

Table 1. Mission Applications Using Pulse Detonation Wave Propulsion

MISSION	PRIMARY OPERATING CHARACTERISTIC (S) REQUIRED	OPERATING MODE(S)
Standoff (cruise) Missiles	High Isp. Long range propulsion, air or surface launched	• Pure air breathing • Rocket mode in multimodel operation for boost, end-game maneuver and terminal acceleration for deeply buried targets.
Target and Surveillance	Compact, low weight, high performance	• Airbreathing and/or • Rocket
RPVs and UAVs	Lightweight, small or modular construction for large UAVs	• Airbreathing and/or • Rocket and air breathing
Air-to-Air Missiles	High Isp and thrust-to-weight, reduced propellant mass, high acceleration	• Rocket and • Mixed air breathing-rocket
RBCCs	Higher thrust-to-weight, higher Isp	• Multimodel rocket-to-air breathing pulse detonation operation-to-Scramjet • Split flowpath
ASAT, Strap-Ons and On-Orbit Maneuver	High Delta-V, launch augmentation and compact, low weight, high acceleration	• Rocket mode

CRITICAL DESIGN CONSIDERATIONS

There are several design issues that must be adequately resolved to bring the pulse detonation wave engine to fruition at its fullest potential.

Inlets

Since a significant portion of the compression process is derived from the detonation wave in the combustor relatively low contraction ratio inlets are possible for air breathing pulse detonation wave engines. Normally, this corresponds to minimum losses in the inlet compression process. However, high quality flow with absolute minimum distortion should be delivered to the combustor to aid in achieving high quality planar Chapman-Jouguet detonations. Furthermore, to ensure that the inlet remains started during the intermittent operation of the engine, steady inlet flow with appropriate isolation and manifolding is required. This requires consideration of modular engine designs.

Air Inlet Valves and Seals

Inlet air valves, when used, are part of the air induction system and must be designed to optimize the inherent valve losses through conversion of the associated turbulence to maximize fine scale mixing in the combustor while achieving the required large scale uniformity of the detonable mixture. Seals for inlet valves (as well as exhaust valves, when used) must also be considered.

Combustor

The combustor is the primary component in the pulse detonation wave engine. Adequate mixing (and vaporization when storable liquid hydrocarbons are used) must be made to occur very rapidly to achieve effective firing frequencies up to the order of 100 Hz. In addition, near direct detonation initiation and propagation must be made to occur reliably using devices whose weight and energy do not significantly impact system performance nor safety.

Other Design Considerations

Controls, guidance, airframe integration including a nozzle, and structural integrity, must also be considered in the design process.

KEY TECHNOLOGY DEVELOPMENT REQUIREMENTS

The initial focus of a technology development effort should be on gaining an improved understanding of the flowpath physics carried out in parallel with the design of a ground and flight test demonstration activity. Current R&D in the US and France suggests that pulse detonation wave technology could be brought to fruition in the near-term through such an integrated effort. The areas addressed here summarize the basic needs with emphasis on operability and performance of a generic pulse detonation wave engine.

Engine Process Control

Several events in engine operation must occur in sufficiently short time increments enabling overall frequencies on the order of 100 Hz. At this rate, the chamber must be filled, detonated and scavenged in about 10 msec requiring that the following processes be made to occur at a sufficiently rapid rate:

a) Filling and mixture preparation through rapid fuel (and oxidizer) injection and micromixing. Adequate macro- and micro- mixing are needed to ensure high quality near planar Chapman-Jouguet detonations. However, the effect of non-uniformities is unknown and data is needed to establish the impact on detonation characteristics.

b) Direct detonation initiation is needed to ensure that maximum pressure is achieved for thrust generation. Currently, detonation initiation requirements are based on highly empirical relationships that need to be extended and validated in rapid fire, highly dynamic environments.

c) Rapid scavenging of combustion products. Although blowdown of the chamber under practical conditions will typically occur well within the 10 msec time duration, the state of the residual products of combustion must be controlled to avoid premature ignition of the subsequent charge.

d) Control of fuel (and oxidizer) injection, inlet and exhaust valve timing, and detonation initiator timing. Timing of these events is critical to the operation and performance of this engine in terms of speed variation and guidance.

In addition to these issues, specific design features are also critical to the successful development of pulse detonation wave engines. For example, separated flows caused by adverse pressure gradients including shock-boundary layer interactions at high speeds and rapid area changes at all speeds must be avoided. Separated regions are characterized by residence times that are substantially longer than duct flow-through times. This means that products of combustion can be "trapped" in recirculating zones and act as ignition sites for the subsequent charge, causing premature ignition. Furthermore, surface temperatures and cooling requirements must be understood and controlled to avoid premature ignition and to define thermal-structural requirements.

Analysis and Test

Because of the numerous interactions of the flow in the pulse detonation wave engine, a purely empirical approach to its development is unlikely. However, it is a prime candidate for analysis and design by CFD methods. Therefore, a primary element of the development plan is the application of an hierarchy of CFD tools that range from an engineering level to a very detailed level to help understand the flowpath physics of pulse detonation wave engines. Experimental requirements will evolve from this effort.

The development effort should begin with a functional analysis that includes mission and application studies. This work will serve to identify roles for the pulse detonation wave engine including stand-off missiles (subsonic and supersonic), reconnaissance missions and target drones, etc. Furthermore, the functional analysis will also help to prioritize the technology requirements for focused applications. Concurrently, the CFD analysis hierarchy must be developed and include features required to treat components of the pulse detonation engine cycle. This should include fuel injection, mixing with oxidizer, detonation initiation and propagation, and scavenging. Experiments to reduce critical uncertainties including direct-connect, semi-free jet and free jet testing must be carried out and be followed by a sequence of flight demonstrations.

Controls

An integral element of a successful development process for the pulse detonation wave engine requires the design of a coherent control strategy for the sub-components and overall engine operation.

SUMMARY

The superior performance potential of the detonation based cycle meets many future military requirements for tactical missiles, in particular the need for higher specific performance and more compact, lower weight designs. Airbreathing and rocket modes of operation are possible providing the capability to self boost for subsonic and supersonic missions. Current R&D efforts suggest that the PDE is a realistic propulsion alternative for low cost tactical missiles, however, several design issues have to be adequately resolved to bring the PDE to fruition at its fullest potential. These include air inlets, air inlet valves and seals, combustor to achieve effective firing frequencies up to the order of 100 Hs, and a coherent control strategy for the sub-components and overall engine operation.

CHAPTER 5

GUN TECHNOLOGY FOR THE 21ST CENTURY

Dr. R.A. Pesce-Rodriguez
Weapons and Materials Research Directorate
US Army Research Laboratory
Author

Dr. W.J. Kolkert
Pulse Physics Laboratory
TNO Prins Maurits Laboratory
Author

ABSTRACT

Conventional solid propellant guns have been around from more than 600 years. While quite a number of significant advances in performance and safety has been realized over this period of time, gun developers are currently in a position where only minor improvements may be expected. In order to meet the need for increased velocity and lethality in the 21st Century, it is necessary to consider unconventional gun systems. Among the systems currently being developed are electric energy guns and liquid propellant guns. While these gun systems offer several potential advantages over conventional systems, they also present many new technical challenges. This chapter gives a brief description of several developmental systems and the specific challenges that must be overcome before their potential for increased performance can be realized.

INTRODUCTION TO ELECTRIC- AND LIQUID-BASED GUN PROPULSION

In the area of advanced gun systems, there are two principal areas of current interest: electric guns and liquid propellant guns. Of these systems, it appears that electric guns are the more likely to become a mature technology by the year 2020.

Electric gun systems (electromagnetic [EM] and electrothermal/electrothermal-chemical [ET/ETC] systems) have the same basic objective (i.e., the acceleration of tactical projectiles to velocities greater than can be achieved with conventional propellants). The major limitation of electric systems is their need for compact, portable sources of large amounts of electrical energy. Currently available technology is insufficient to support the energy needs of these systems.

In general, electromagnetic rail guns function by means of a magnetic force on a moving current element (the armature). Depending on the type of armature used, the resulting rail gun can be placed into one of three categories: solid armature rail guns, plasma armature rail guns, and hybrid armature rail guns.

In the electrothermal category, there are at least two possible subsystems, i.e., pure electrothermal systems, which use only electric energy to heat propellant gases, and electrothermal-chemical systems, which use electrical energy to initiate chemical reactions that provide the bulk of the energy ultimately available to move a projectile. Both ET and ETC technology are considered to be "near term" since their hardware and interior ballistics are relatively similar to conventional systems. For this reason, ET and ETC systems are of interest to nations that currently produce conventional large-caliber artillery.

Interest in liquid propellant systems has historically been driven by the desire for a remotely operated weapon where the advantages of a liquid propellant could be effectively utilized. Among these advantages are: reduced facilitation and propellant costs; increased logistic efficiency and effectiveness; increased safety throughout the military system, including reduced vulnerability on the battlefield; simplified gun automation; and increased gun performance and effectiveness.

Of the possible configurations of liquid propellant guns, two designs have been foremost in interest: the bulk-loaded system and the regenerative system. Bulk-loaded systems, while mechanically simple, lack the ballistic control necessary for practical implementation. Regenerative systems, on

the other hand, have demonstrated performance equal to that of conventional solid propellant systems through mechanical control of the interior ballistic process.

ELECTROMAGNETIC LAUNCHERS

Electromagnetic guns fall into two basic classes: rail guns and coil guns. These differ in the geometry of achieving confined magnetic fields and coupling the resultant forces to achieve projectile acceleration as schematically shown in Figure 1. Compared to coil guns, rail guns are, as a rule, conceptually and geometrically simpler and have lower impedance (i.e., require higher current and lower voltage for a specific propulsion task). They have received far more developmental attention, despite the potential for greater energy efficiency from coil guns. Coil guns become more attractive at larger scales due to more efficient coupling and the difficulties associated with precise switching that may impose velocity limits lower than those for railguns.

Rail Launchers (Rail Guns)

For firing conventional munitions at conventional velocities, potential advantages of electric energy weapons systems include improved survivability, decreased logistics burden, real-time adaptation of ballistic performance to the threat, extended munitions options and improved operational use, reduced maintenance cost, improved expected lifetime, and robotization.

For firing hypervelocity munitions, advantages of electric energy weapons systems include improved hit probability; new kinetic energy (KE) munitions concepts; improved conventional kill probability; enlarged engagement range; and multifunctional role in air, sea, and land combat.

Hypervelocity launch using rail launchers has been demonstrated by a large number of laboratory experiments. Gram size projectiles have been accelerated to velocities in excess of 7,000 m/s and new projectile designs of 1 kg have been accelerated to a velocity of 4,200 m/s. A standard armor-piercing fin-stabilized discarding sabot (APFSDS) projectile, with a launch package mass of 3.55 kg has been successfully accelerated with a 90-mm bore, 7.5-m rail accelerator to a muzzle velocity of 1,985 m/s (Defense Research Agency [DRA], UK) at a launch efficiency, η, of 0.27 (η = ratio of the electromagnetic energy commutated into the accelerator and the KE at the muzzle). [Note: muzzle velocities for a "typical" 120-mm solid propellant gun is on the order of 1,600 to 1,700 m/s]

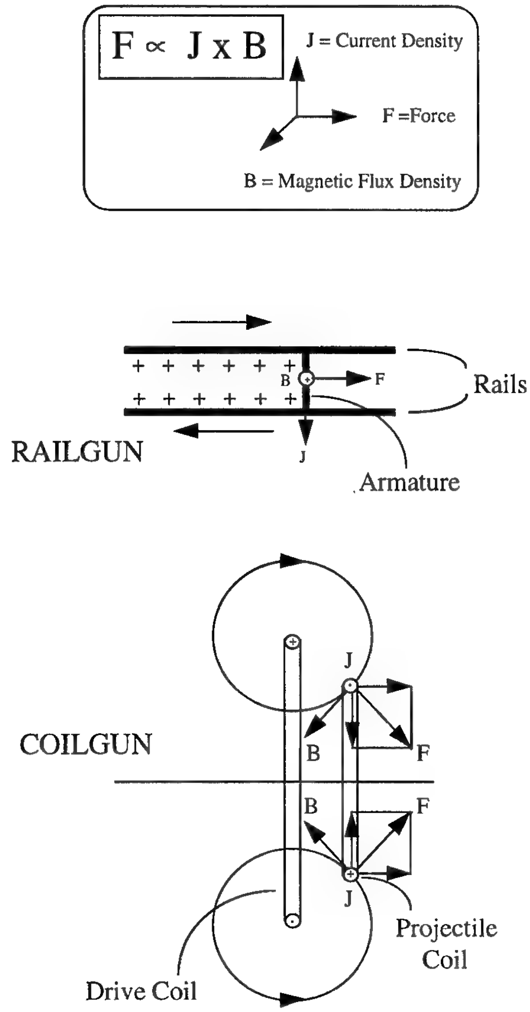

Figure 1: Generic geometries, magnetic fields, and forces in the rail gun and coil gun

First steps to weaponization have been made. Large caliber rail accelerators (ϕ 90-mm bore, 7-8 m, mass = 2.8 kg) have been designed and are being tested in the USA. New materials (e.g., ceramics and ultra strong fibers) are being applied in these applications.

A complete medium-caliber (30-mm round-bore equivalent) rapid fire electromagnetic weapon system, including the pulsed power supply (total system mass is approximately 1,500 kg) has been

designed and constructed (USA). Component tests are being pursued with launch experiments resulting in muzzle velocities up to 1,780 m/s and η of 0.35 for 180 g projectiles.

The primary challenge to successful fielding of an electromagnetic gun system is the need for compact energy storage and power supplies. For a typical ordnance muzzle velocity of 20 MJ, 60 - 80 MJ must be provided to the gun breech for each shot. This is a significant power requirement. For repetitive-firing weapons, energy storage and power supply requirements are even more demanding. To try to meet these demands, a considerable amount of effort has been and is being expended in the area of capacitors and rotating machines. While there have been many advances in capacitor technology, they have not been significant enough to expect an electromagnetic gun system to be fielded in the very near future.

Another challenge in the area of rail launchers is wear. Regardless of the type of armature used (solid, plasma, or hybrid), friction-limited velocity and concomitant rail wear are serious concerns. Of the three types of armature systems, wear is the least serious with the solid armature-based systems, which are characterized by a higher efficiency, and therefore by reduced wear. With further refinement, this technology may find a place in tactical warfare applications. Plasma-based armature systems suffer from poor efficiency at low velocity and experience significant resistive energy losses in the plasma. Hybrid armature-based systems make use of a solid metal main armature body with a thin layer of plasma that serves as an interface between the rail and the armature. The main obstacle for this technology is the problem of rail surface damage resulting from power dissipated in the plasma contact.

For military application of rail accelerators, an arc-erosion-free launch process followed by a controllable transition behavior resulting in plasma boundary layers at the rail armature interface is required. For "transitioned armatures," which occur when there is an uncontrolled electrical arc between one or both armature faces and the adjacent rail, velocities as high as 1,200-1,400 m/s have been achieved (TNO, the Netherlands). Deposition of armature material and arc-erosion is unacceptable for repetitive operating rail guns. Research and development on the armature transition process are needed to proceed to fieldable rail guns, Moreover, improvement of the accelerator design with respect to weight per unit length must be made. Strong and lightweight materials will play an important role.

Weight and size of pulsed power supplies and switching systems have to be reduced to make transportable electromagnetic rail systems possible. Together with compulsators, fast discharge bipolar batteries, pulse transformers, and SiC-based semiconductor opening switches look very promising to this end.

Linear Induction Launchers (Coil Guns)

The propelling force for induction launchers is created by the interaction of a current and a magnetic field. The primary advantage of these launchers is that current does not have to pass through a moving contact from the external structure to the armature. The main difference between these systems and rail guns is that the magnetic field for coil guns is generated by an applied driving current. For rail guns, the same current flows in the rail and the armature. The drawback for induction launchers is that they require a complex design of coils and power supplies as well as of control for synchronization of the coils. The requirement of extremely large power and rapidly increasing frequency have thus far proven to be an insurmountable hurdle for generators and for most power conditioners consisting of capacitor bank and switches. The issue of control of induced current distribution has also yet to be sufficiently addressed.

Among coil gun concepts, the coaxial traveling-wave launcher appears to be superior, in that it has uniform distribution of propelling and centering forces along the complete armature surface during acceleration, as opposed to aft pushing. In addition, there is no need for exact synchronization between projectile and drive coils. The main disadvantage of coaxial traveling-wave launchers is the cost of the required alternating current capacitors and switches.

ELECTROTHERMAL LAUNCHERS

"Pure" Electrothermal Launchers

Pure ET guns use only electrical energy to heat propellant gases. These guns have energy requirements of the same order of magnitude as those of electromagnetic guns and, therefore, face similar challenges with respect to development of power supplies. Pure ET gun technology involves the use an inert propellant (e.g., water) whose only function is to provide a low molecular weight working fluid when heated to evaporation or decomposition. In general, it has been found that the energy required to

evaporate the working fluid is so large as to make such gun systems nonweaponizable using near-term electric power technology.

Electrothermal-Chemical Launchers

The main advantage of ETC systems is that they can, with minor modifications, utilize existing gun hardware. They are often considered an "upgrade" technology because the gun tube and interior ballistics resemble those of conventional guns and because power supplies needed are approximately one order of magnitude smaller than for electromagnetic systems and, therefore, are more readily vehicle-integratable. They differ from pure ET systems in that inert propellants are replaced with energetic propellants. A schematic of such a system is shown in Figure 2. Compared to conventional powder systems, these guns offer increases in range (in excess of 50 km) and have the potential to deliver 140-mm performance from a 120-mm gun system. Increases in lethality, based on hypervelocity and novel projectile designs, are also possible. Challenges that remain to be addressed for these systems include demonstration of performance commensurate with conventional powder gun; identification of propellants with not only specific energy density superior to currently fielded formulations, but which also satisfy safety, insensitive munitions requirements, and manufacturing requirements; control of plasma/propellant combustion; and moderation of propellant temperature coefficient.

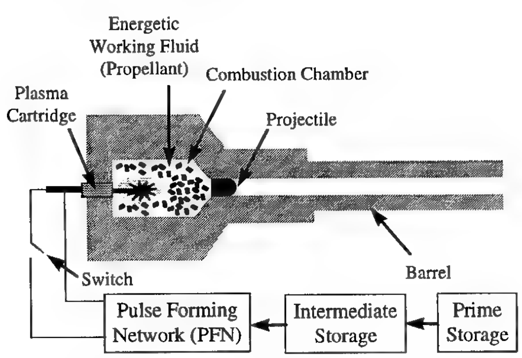

Figure 2 Schematic of an electrothermal -chemical gun

One current topic of research in the U.S. is the interior ballistic cycle of ETC guns. The goal is to identify potential mechanisms that may contribute to observed shortfalls in performance. Two main categories of mechanisms are of particular interest: those mechanisms in which energy, either from electrical or chemical sources, is bound in such a manner as not to be transformed into useful thermal energy during the ballistic cycle; and those mechanisms that result in changes in the hydrodynamics expected of a typical powder gun (e.g., the pressure gradient). Special attention is being paid to examination of plasma capillaries, which are considered to be critical elements in the conversion of electrical energy to thermal energy. Recent investigation of radiant losses by plasmas to chamber/gun walls has revealed that this should not be a serious concern.

Given the early stages of ETC research, it is difficult to make substantive statements regarding the characteristics of a system yet to be defined. This is also the case for electrical power supplies since so little is known about the sensitivity and vulnerability of existing components, much less the increased energy and power density components required in the future for tactical applications of electric guns.

With all its potential limitations and uncertainties, ETC propulsion continues to hold potential for substantial systems benefits. Existing data are inadequate to support rational projections of technology maturation. However, if current technical objectives of on-going programs in several nations are met over the next few years, development of an ETC gun during the first decade of the next century may well be possible.

LIQUID-PROPELLANT-BASED GUNS

The key technical and engineering challenges for the liquid propellant gun fall generally into gun and propellant categories. In the gun area, the presence of high-frequency pressure oscillations in the combustion gases is the key near-term technical challenge. These oscillations are not related to the lower frequency, longitudinal pressure waves that are responsible for breech blows in conventional solid propellant guns. The primary concern raised by the presence of these oscillations is their effect on sensitive projectile components (e.g., fuzes) rather than on the potential for combustion anomalies or gun damage. In the long term, the key developmental engineering challenge of the regenerative liquid propellant gun (RLPG) is reliability in the field environment. In the propellant area, the primary challenge is the engineering and design of the components and infrastructure that will facilitate successful integration of a liquid propellant into the

field. These include not only production facilities, storage and transportation containers, handling equipment, etc., but also the new procedures and doctrine necessary to optimize operations with a liquid propellant. Emphasis must be given to systems design in order to exploit the reduced sensitivity characteristics of the liquid propellant (LP) and optimize safely and vulnerability reduction.

Bulk-loaded Liquid Propellant Guns

Although many problems have occurred in tests of bulk-loaded LP guns, the appeal of a LP charge continues and is based, in part, on the potential design flexibility of a liquid system that might be used for generating a variable charge for producing on command either a lethal or a nonlethal charge. Methods for controlling the combustion of bulk-loaded guns include three general approaches (i.e. the development of a repeatable functioning ignitor, the use of chamber geometry for reducing instabilities associated with the gas-liquid interface, and multipoint ignition). In the USA, the propellant of choice is XM46, a hydroxylammonium nitrate-based monopropellant that is relatively insensitive to various ignition stimuli.

Control of the early combustion is a necessary condition for avoiding an initially low gas generation rate, a problem that has been directly implicated in catastrophic failures of bulk-loaded LP guns. The other extreme, an initially high gas generation rate, can also result in problems associated with exciting large amplitude pressure waves.

The uses of unconventional chambers include two approaches: stepped chambers and multicelled chambers. The stepped-chambers approach shows that the volume of propellant adjacent to the ignitor is an important control parameter that can be used for shaping the pressure-time curve. Based on modeling studies, the chamber steps located downstream of the ignitor may introduce localized turbulence that promotes a more rapid radial burn, thereby limiting the penetration of the initial gas cavity and, hence, the instabilities associated with gas-liquid mixing, a suspected source of variabilities in past bulk-loaded firings.

Regenerative Liquid Propellant Guns

A simple RLPG is depicted in Figure 3. It consists of a standard gun tube attached to a chamber that contains the regenerative piston. The head of the regenerative piston divides the chamber into two sections: a combustion chamber and a propellant reservoir. The length of the reservoir and, thus, the reservoir volume and maximum piston travel, are defined by a breech element through which the piston shaft extends. Cylindrical injector orifices are located in the head of the piston. These orifices are initially sealed to prevent leakage of the propellant into the combustion before ignition. An ignition train (consisting of a primer, ignition charge and, in some cases, a booster charge) completes the system. Although recently the US Army has shifted attention away from LP guns for its Advanced Field Artillery System due to schedule and cost considerations, there have been several notable accomplishments by that LP program, including a demonstration in ballistic repeatability approaching that of solid propellant guns, a demonstrated range firing in excess of 40 km, development of a predictive multidimensional model, rapid transfer of an LP from the reservoir to the combustion chamber at high mass flow rates, and the integration of all required support systems into a test stand. As in any development program, various problems were encountered and, in some cases, resulted in substantial damage to test hardware. Most problems fall into two general categories: operational and combustion.

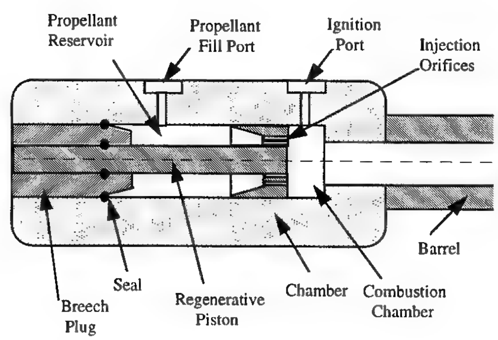

Figure 3 Schematic of a simple in-line regenerative test fixture.

Examples of operational problems in the USA include a reservoir to gun chamber leak resulting in a partial bulk-loaded firing and a pre-ignition of the charge during propellant transfer into the reservoir. The first example caused minimal damage to the gun. The test is of ballistic interest because of an abnormally high rate of pressure rise that resulted in a high performance firing with a constant pressure coefficient of 0.95. [Note: an ideal conversion of chemical energy to KE would give an

exponent of 1.00.] The second example of an operational problem was an incident that resulted in damage to the gun and was caused by what is believed a material incompatibility problem. The propellant used in the 155-mm program is XM46, a hydroxylammonium nitrate based monopropellant. This propellant offers many safety advantages, however, its incompatibility with many materials, including transition metals, increased the system integration risk. During transfer, the propellant came in contact with a damaged transfer fill line where propellant was likely exposed to an incompatible material.

The second category of problems is related to combustion. Examples include the injection of propellant from a liquid propellant ignitor that may result in large amplitude pressure spikes, and the hydrodynamic response of the propellant reservoir to the ignition and early combustion during start-up. The first example of a combustion-related problem involves the coupling between the hydrodynamics and combustion that may result in large amplitude pressure spikes. Based on multidimensional studies, this type of problem is believed to be associated with a local build-up of partially burned or unburned LP, especially during the early start-up. More effective dispersion of the injected propellant and better control of the propellant decomposition during start-up through the use of chemical additives are approaches that may avoid this problem. The second example of a combustion related problem is related to a compliant system that is not adequately damped, which may excite low-frequency pressure waves, especially during start-up. Some evidence suggests that these low frequencies may contribute to piston reversals. The LP program has formulated the guidelines for the successful development of an alternative propulsion gun system. Although various problems were encountered, the advances made during the program demonstrated the feasibility of a large scale gun where a liquid propellant could be transferred at high loading rates and successfully fire a projectile under remote operation and with controlled combustion. Designs based on advanced interior ballistic and finite element stress models were developed that could be used to support development of either future liquid propellant man-operated weapons or to support development of remotely fired weapons where the advantages of a liquid propellant could be effectively utilized.

SUMMARY

To overcome the challenges facing both electromagnetic and electrothermal gun propellant systems, efforts in the area of compact energy storage and pulsed-power delivery must continue. For electromagnetic gun technology to reach maturation, resources must also be focused on concerns related to wear and to the containment of pulsed power supplies (in the event of failure). For successful fielding of a liquid propellant gun system, additional research in the area of ballistic control and liquid propellant service life must be pursued. In view of the challenges faced by all three major gun propulsion technologies, it appears that the electrothermal chemical should be regarded as the most likely near-term option of the three gun system candidates.

CHAPTER 6

LASER POWER BEAMING: AN EMERGING NEW TECHNOLOGY FOR POWER AND PROPULSION IN SPACE

Dr. H. E. Bennett
Bennett Optical Research, Inc.
Author

Dr. K.C. Schadow
Naval Air Warfare Center, Weapons Division
Editor

ABSTRACT

The potential of laser power beaming from a ground-based laser to satellites is discussed. The laser power may be used for propulsion and to increase the electric power available from the satellite. The increase relative to solar power generation can be an order of magnitude using the same size solar panels. For propulsion, it is proposed to beam the laser power through the atmosphere to a "tug satellite" which carries launched satellites to a higher orbit. The increased satellite electric power may be used to provide surge power to inhibit jamming of satellites in wartime, to overcome the increased atmospheric absorption in microwave operations, to provide orbit changes or corrections, to extend station keeping and satellite lifetime, and to transport malfunctioning satellites to the Space Station for repair and reinsertion in orbit. Key elements in the proposed concept include a 100 to 200 kW free-electron laser, a 3 km long underground ultra-high vacuum tube and a novel adaptive optic telescope. All elements in the concept have either be demonstrated or prototyped.

INTRODUCTION

The technology for putting satellites into orbit and keeping them operational is an important consideration for the 21st century. Satellites in space are a key to military communications, surveillance and navigation. At present there are severe limitations to how much power is available for use in space and on orbit correction, lifetime extension and moving or repairing satellites, particularly those in high earth orbit beyond reach of the Space Shuttle. This paper deals with laser power beaming to satellites and the conditions under which those limitations may be relaxed using this novel technique.

It may be helpful to enumerate briefly why satellites are so important. They provide the backbone of almost all of our modern communication technology. They are crucial to long distance radio, television (video communications), and telephone (long distance as well as cellular phones). Cellular telephones will be more and more widely used for both civilian and military applications. In the future they will have better and better coverage (no blind spots where communication is impaired or impossible) as more satellites are placed overhead. About 75% of U.S. military communications overseas are handled by satellite and 90% of communications to the U.S. Navy fleet are handled by satellite (Ref. 2).

In addition, satellites are key to both battlefield surveillance and to monitoring hostile or friendly activities worldwide. Solar power is now the only power source available to operate satellite surveillance systems. If additional power were available, an all-weather battlefield radar surveillance net could be mounted. During the cold war the Russians spent millions of rubles trying unsuccessfully to develop a satellite nuclear power capability for an all-weather radar satellite surveillance system. The alternative to that power source is laser power beaming, the subject of this paper.

Another function of satellite surveillance both in a battlefield and elsewhere is weather prediction and analysis. Weather satellites provide vital information that indicate rain, snow, cloud cover and expected wind direction and aids in predicting hail, hurricanes, tornadoes, and perhaps wind shear conditions. In wartime such information can be vital.

Global Positioning System (GPS) satellites currently provide two accuracy systems, one for commercial and one for military use. The system accuracy for personal hand-held or built-in GPS receivers for private and commercial aircraft, private power and sail boats, ships at sea, hikers, bicyclists, and automobiles is on the order of a few yards. They may even be useful for evaluation of the earth platelet movements leading to the prediction of earthquakes. This dual use program is a good example of how civilian uses can help to underwrite military system costs. The price of personal hand-held commercial systems that are available is as low as a few hundred dollars. These types of receivers were widely used in the Gulf War.

The military have a more accurate coded operational system. The many military uses of GPS position sensing include aircraft and ground navigation, accurate determination of friendly troop locations, and locations for real-time surveillance video of battlefields day or night from unmanned aircraft vehicles (UAV). Ships at sea, landing craft and other navy vessels can use GPS as well as battle tanks, jeeps, forward air strike directors, etc.

There are some uniquely military satellite problems which are not duplicated in the civilian sector but to which laser power beaming can make a contribution. Examples are moving geostationary satellites in orbit over a battlefield; providing boost power for ship navigation, aircraft and missile systems using GPS; and obtaining high resolution images of space objects.

Two factors dominate all other space development issues, namely (1) the cost of space transportation and logistics, and (2) the availability of operating power. Since the cost per pound of putting anything into high orbit is very large (presently about \$72,000/lb. to geostationary orbit), the level of commercial and government utilization of high earth orbits is significantly constrained. Launch costs for a satellite to geosynchronous orbit are typically \$80 to \$100 million or more. Moreover, since power generation and storage systems are relatively heavy and thus very costly, the magnitude of all activities in space is further constrained by shortage of power. Large satellites always seem to be power starved. Figure 1 illustrates the power usage of a typical commercial satellite family as a function of the time at which they were placed into service. The most recent satellites in this series utilize twice the power of the highest point plotted. However, if we accept the idea that solar panel size has for all practical purposes peaked out, this exponential growth cannot continue unless a new idea is developed for supplying the necessary power.

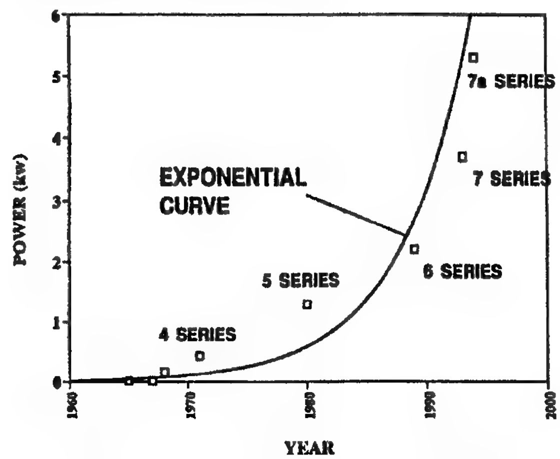

Figure 1 INTELSAL Telecommunication Satellite Power Growth

LASER POWER BEAMING

Laser power beaming may be the answer both for propulsion and for supplying the additional power needed to operate future satellites once they are in orbit. To supply propulsion, laser power is beamed through the atmosphere to a "tug satellite" which carries the just launched satellite to higher orbit. In this way, carrying up large amounts of fuel into space to supply the thrust for this operation is avoided. Once in orbit the laser provides the power needed to operate the satellite.

Today's satellite batteries are powered by photo-electric solar panels that convert sunlight into the electricity needed for satellite operation. If we assume that the panels have reached their maximum functional size, a tug, which would operate best with a much larger amount of energy than present solar panels operated in the usual way can supply, is possible but not very attractive. However, additional efficiencies are possible in the solar panel area. The silicon battery cells used by most satellites convert

13% or less of the sun's energy into electricity (Ref. 3) and the more expensive, less frequently used gallium arsenide cells convert 18.5% of the sun's energy(Ref. 4). By choosing a laser wavelength to increase the efficiency of photoelectric generation within the cell and also by increasing the power density on the cell, laser power beaming will provide over ten times as much electrical power to a satellite as the sun without overheating the satellite solar panels (Ref. 5). Laser power beaming thus provides a means for both increasing the power available for satellite operation and for efficiently using an inductive thruster ion engine instead of a rocket engine to provide the propulsion for sending a satellite from low earth to high earth or geosynchronous orbit at significant reduction in cost.

The National Aeronautics and Space Administration (NASA) name for this laser power beaming concept is Space Laser Energy (SELENE). Selene was the Greek goddess of the moon, and the concept may ultimately be the key technology needed to power a moon station. NASA studies conclude (Ref. 6) that launch costs to geosynchronous orbit could be reduced by a factor of three by using a space tug and SELENE. The light energy beamed from the ground, where power is cheap, is converted into electrical energy in space and used to power the inductive thruster on a "space tug" satellite. That satellite will make a rendezvous with a satellite which has been launched into low earth orbit and tow it into the desired higher orbit using power from the inductive thruster engines. The tug may also move a satellite in geostationary orbit from place to place over the earth. Such rendezvous techniques were demonstrated by the Space Shuttle when it rescued the malfunctioning INTELSAT 6 in low earth orbit, corrected its second stage rocket and successfully sent it into geosynchronous orbit in 1992. Figure 2 shows the INTELSAT 6 at the rendezvous site and the astronauts preparing it for relaunch.

Satellites in geostationary orbit could also be moved quickly and relatively inexpensively to another site using the tug. Such moves, which are of special interest to the military, are now very expensive. One satellite moved over the Persian Gulf during the Gulf war took several months to position and cost tens of millions of dollars. Since the earth is not quite round a satellite in geostationary orbit does not remain stationary relative to the earth by itself. Geostationary satellites are supplied with station-keeping rockets which are periodically fired in a controlled manner to keep the satellite stationary. To make the transfer to a position over the Persian Gulf, the geostationary satellite used its station-keeping rockets to propel itself, thus significantly shortening the satellite's effective life in space. Once the fuel for the station-keeping rockets is exhausted, the satellite must be abandoned and a new one must be launched. At present there is not way to move a satellite in high earth orbit except by using the satellite's own rockets. By using laser power beaming the satellite could have been moved quickly and relatively inexpensively. In addition, laser-powered station-keeping thrusters can be used on new satellites in place of the heavy rocket thrusters, increasing the expected life of the satellite in orbit or reducing its weight significantly.

- **WEIGHT 2650 KG (MAX 4170)**
- **PAYLOAD 500 KG (MAX 662)**
- **INITIAL OUTPUT POWER 3500 W**
- **SOLAR AREA 12 M^2**
- **BATTERY AMP HRS 19-200**
- **DESIGN LIFE 12 YRS**
- **LAUNCH ATLAS, ARIANE, PROTON, TITAN, SHUTTLE**

CAPTURE OF INTELSAT 6
BY SHUTTLE 1992

Figure 2 INTELSAT Communications Satellite Ready for Relaunch into Geosynchronous Orbit

Some mass, in the form of a gas, must be carried up into space even if laser power beaming is used. However, the thrust per unit mass of fuel is much greater if laser power beaming is used. However, the thrust per unit mass of fuel is much greater if laser power beaming is used than for a conventional rocket. Unlike conventional ion thrusters, which often use a heated filament, enough mass of ionized gas is ejected to produce significant total thrust. In operation, the laser beam irradiates the solar panel, generating approximately ten times the electrical charge obtainable over the same period from the sun. A capacitor is charged, which discharges through an inductive coil and ionizes the small amount of gas fed above the coil. The ionized gas is ejected

producing the thrust. The parameter I_{SP}, which is a measure of the relative thrust per unit mass, is about 2500 as compared to 480 for a conventional rocket (Ref. 7). This factor of 5.2 explains why a lower mass of fuel must be carried than if a rocket were used for station-keeping or, alternately, why with the same mass of fuel the lifetime of the system is significantly extended. There are several variants to this idea, at least one of which is now commercially available for space applications.

The SELENE program calls for an array of six ground stations that would provide nearly complete global coverage to space (Ref. 7). This means that at any given time, a particular satellite will be in the line of sight of one or more of the laser ground stations and could therefore receive power from the earth. A prototype station is to be installed in the mountains near China Lake, California. This site is believed to be the best place in the continental United States for such a system (Ref. 8). This unpopulated area is close enough to the equator to reach most of the geosynchronous satellites over the United States, has the most cloudless days (260/year) of anywhere in the country (in 1993 when the clouds were monitored continuously at the site there were only five completely overcast days all year), is centered in one of the largest restricted overflight areas in the country, has visibility which is often over 100 miles and astronomical seeing which is world class, has the largest geothermal electric power plant in the country nearby as well as a large coal-fired electric power plant with surplus capacity, and has plentiful water for cooling from wells in the China Lake playa or from reprocessed water which could be piped from the City of Ridgecrest. Ridgecrest, a highly technical community supporting the largest research, development and testing facility in the Navy, has a population of about 30,000 and is 45 minutes by air from Los Angeles International Airport.

The proposed SELENE system, shown in Figure 3, consists of:

1. a 100 - 200 kW free-electron laser providing reliable high power operation at significantly reduced cost,
2. an underground vacuum tube perhaps 3 km long that allows the tiny 1 mm diameter high quality beam at the output of the laser to expand by diffraction to a beam diameter of about 3 m, which can then be handled by conventional optics,
3. the novel adaptive optic telescope design with a 12-meter diameter multi-element primary mirror to project the laser beam into space, and
4. the satellite, which contains a beacon allowing the adaptive optic telescope to sense the returning wavefront and correct the outgoing beam for atmospheric distortion.

A prototype of the free electron laser is now under construction in Novosibirsk, Russia, and is scheduled for completion in 1998. Parts for the

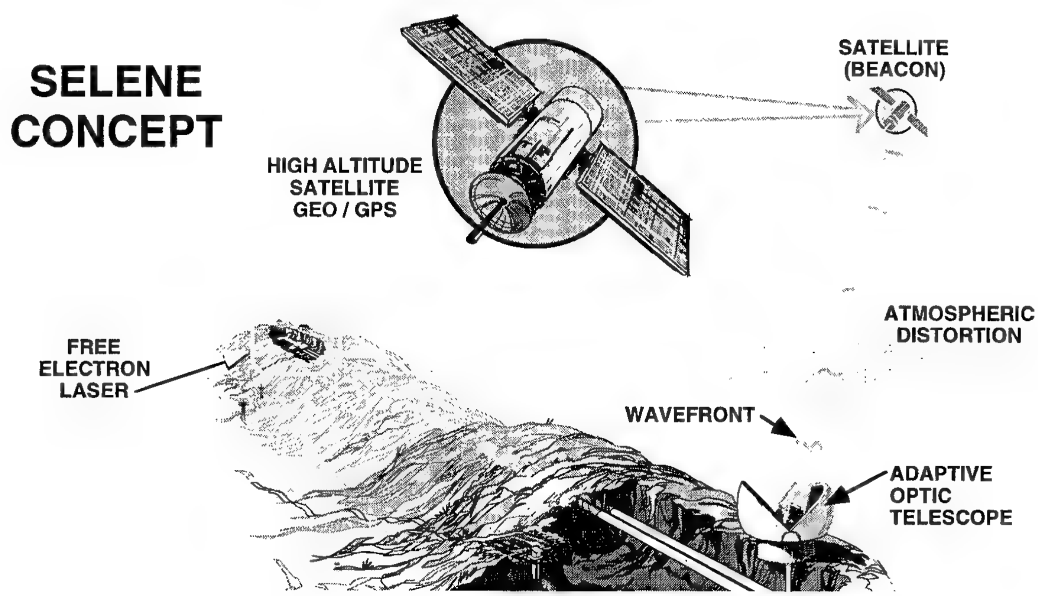

Figure 3 Laser Power Beaming Facility - SELENE System Concept

China Lake laser will be sent from Novosibirsk to the Lawrence Berkeley Laboratory and assembled into a laser, then reassembled at the China Lake site. This laser will be completed five years from the date of program initiation. It will be coupled to an adaptive-optic telescope used to transmit the laser beam. The satellite could be outfitted with a low-power diode laser beacon mounted in front of the satellite to compensate for the change in isoplanatic angle. It would send a pilot beam to the ground station. Alternately an artificial guide star could be used to perform the atmospheric compensation. A wavefront analyzer at the telescope will derive information to correct the outgoing laser beam based on the incoming signal from the satellite laser or guide star. Any wavefront aberrations introduced by the atmosphere will be sensed and canceled as the output free electron laser beam traverses back through the same atmospheric path traversed by the light from the diode laser or guide star. Sampling rate will be between one and ten millisecond since the shortest time constant of atmospheric distortion is of this order. The laser beam will thus arrive at the satellite with minimal distortion. This concept was demonstrated in an experiment (Ref. 7) conducted at Mount Haleakala in Hawaii in 1990. The target satellite carried a beacon. Light from this beacon was detected and analyzed at millisecond intervals. The wavefront of the outgoing beam was then distorted in such a way as to exactly cancel the distortion introduced by the atmosphere as the beam went up to the satellite. The demonstrated ability to perform this cancellation is a key to the success of SELENE.

In order to effectively beam laser power into space to power satellites in mid or high earth orbit, very large mirrors (perhaps 12 m in diameter or more) and an adaptive optic system to penetrate the atmosphere are required. Primary mirrors with adaptive optic segment sizes less than the equivalent Fried coefficient for atmospheric turbulence (typically 3-5 cm at zenith in the visible for normal sites, 20 cm or more for excellent sites) are optimum for atmospheric penetration. These new mirrors may have over one hundred thousand segments, each with its own computer driven adjustments. The idea has been described as a marriage of optics and Silicon Valley. The computational problem that this approach generates is believed to be solved (Ref. 9). Large mirrors composed of phased segments only a few cm in diameter are a new concept in optics. They offer the possibility of beaming laser power to space with minimum atmospheric distortion using relatively inexpensive very large mirrors. Such mirrors would have light-gathering power nearly 20 times greater than the Hubble space telescope. NASA has been investigating such mirrors since 1991 and has built a small operating prototype at Marshall Space Flight Center (Reference 10). Since they will be quite light., the mirror mount designs used for the Layton radio telescope designed at California Institute of Technology will be used for the completed mirror. An alternate design was developed during the Cold War and was successfully used to beam power to a satellite (Ref. 10) from San Diego, California, a most difficult site. These new classes of optics offer new possibilities in astronomy and may change the way we look at telescopes for space.

SUMMARY

The potential of laser power beaming furnishing power and propulsion in space for military as well as civilian applications is very attractive. It is an ideal dual use program. Advantages are:

1. launch costs to geosynchronous orbit can be cut to less that one third of present values;
2. satellites can be moved quickly and inexpensively from one position to another without reducing their life expectancy;
3. errors in orbit can be corrected without abandoning the satellite;
4. if the satellite malfunctions it can be repaired in space;
5. aging satellites can be given a life extension by power beaming additional energy to them to supplement what they can receive from the sun and
6. on demand output power boosts of an order of magnitude can be obtained for GPS or other satellites which are being jammed by adversaries. (This objective is achieved by laser beaming additional power for temporary storage on the satellites to be released on call even when the satellite is on the other side of the world.)

Although the cost of setting up a laser power beaming system is fairly large, about $2B for the complete 6 site system, and some development work on the components is still required, the potential returns on investment make it both an attractive business and an attractive government venture. The implications for control of space in wartime by NATO security forces are significant, particularly if

the development were done in a non-NATO country, and should be considered seriously.

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14. Abstract

The report provides an overall projection and perspective of possible propulsion and energy technological capabilities.

The "Hypersonic Air Breathing Missile" is propelled by a liquid hydrocarbon fueled scramjet engine for Mach numbers of 5-8. An Overview of merits, payoffs and critical technology development and demonstration needs of such an air breathing hypersonic missile, and Key Technology Development Requirements are presented.

Technology Overviews are also presented on:

- turbomachinery propulsion;
- advanced technology capabilities expected in rocket propulsion;
- a special propulsion concept for possible tactical missile application called the pulse detonation wave engine;
- some advanced technologies associated with gun propulsion and its potential impact on the future warfighters' capability;
- laser power beaming for satellite positioning and on-board power enhancement.

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